Defense Threat Reduction Agency
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TECHNICAL REPORT

Regional Small-Event Identification Using Networks and Arrays of Seismic and Acoustic Sensors

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April 2006

DSWA01-97-C-0153

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Our work under this contract has had three primary objectives, but with the common theme of using seismic data to distinguish mining blasts from all other event types. We have used spectral characteristics of whole waveforms to to discriminate industrial blasts from instantaneous explosions and earthquakes. We applied the automated time-frequency discriminant (AFTD) to several datasets to test transportability and robustness of the algorithm. The main conclusions of this work, described in the first section of this report, are that the method can be applied without significant modifications to broadly distributed datasets, but the method has limited range due to attenuation. In the second section, we describe our use of seismic waveforms between .05 and 10 Hz to characterize well ground-truthed mine blasts in Wyoming. Included in this section is preliminary modeling of events in this region. The report's third section summarizes the main findings of a review article written by Brian Stump, the PI, Craig Pearson and Vindell Hsu and published in the Reviews of Geophysics [40(4), 1011, doi:10.1029/ 1998 RG000048, 2002]. In this article, we assess the state-of-the-art in global monitoring of mining blast activity and explore avenues for further research needed in this area.

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TO GET ← BY ← DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 ($kg\text{-}m^2$)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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Acknowledgements

Section 1:
The datasets were provided by numerous people. Lori Grant provided the European Ground Truth Database which included data donated by J. Wuster. The NORESS data was made available by Tom Sereno at SAIC. The KNET and NRDC datasets were provided by Frank Vernon. Peter Goldstein and Steve Jarpe at LLNL provided the Nevada data. Rob Mellors provided information on the limestone quarry in Kyrgyzstan. A careful review by Peter Goldstein and an anonymous reviewer is appreciated. This research was funded AFTAC under contract F19628-95-K-0012 and DTRA under contract DTRA01-97-C-0153.

Section 2:
The combination of regional and close-in measurements for solving problems related to mining explosions could not have been made without the close collaboration with Vindell Hsu at the Air Force Technical Applications Center (AFTAC). Bob Martin, David Gross, Al Blakeman and Terry Walsh at the Black Thunder mine provided essential support. Portable deployments were made possible by CL Edwards, Diane Baker and Roy Boyd (LANL) and Adam Edelman, Aaron Geddins and John Unwin. The authors would like to thank Doug Baumgardt and an anonymous reviewer for helpful comments. Funding and equipment provided by LANL (under contracts 1973USML6-8F and F5310-0017-8F) and the efforts of Frank Vernon and the IGPP north lab permitted us to deploy the azimuthal network. Data processing and analysis by MAHH was funded by DTRA under contract DTRA01-97-C-0153 and LANL under contract F5310-0017-8F.

Section 3:
This work has involved critical contributions from many individuals. The personnel at both mines, Bob Martin, Dave Gross, Al Blakeman, Terry Walsh, and Chris Frandsen, provided exceptional support in the mines and insight into modern blasting practices. Portable instruments were deployed by Los Alamos National Laboratory - C L Edwards, Diane Baker, Roy Boyd, University of California San Diego - Adam Edelman, Aaron Geddins and John Unwin, and Lawrence Livermore National Laboratory - Phil Harben and Don Rock. The field crew provided excellent data and sparked important discussions that led to the resulting analysis. Funding and equipment provided by LANL (under contracts 1973USML6-8F and F5310-0017-8F) and the efforts of Frank Vernon and the IGPP north lab permitted us to deploy the azimuthal network. Rod Whitaker (LANL) provided valuable advice on the portable infrasonic deployment at MNTA. Several of the images in this report are attributable to David Anderson at Southern Methodist University. David's interest in combining diverse data sets in order to provide new understandings of important physical processes is noted. We also would like to acknowledge the support in data collection and data analysis provided by the Pinedale Seismic Research Facility (PSRF) of AFTAC. Special thanks go to Sgt. Vince Gillen and Sgt. Bruce Hawley for fieldwork and contact of local mining companies. The interest in regional observations and logistic support by the PSRF contributed greatly to this work. Reviews by William Leith, Rod Whitaker, John Orcutt and Bernard Minister greatly improved this section. Work on the review paper upon which this section is based for two of the authors (BWS and DCP) was performed under the auspices of the US Department of Energy by Los Alamos National Laboratory under contract W-7405-ENG-36. MAHH was funded by AFTAC under contract F19628-95-K-0012 and DTRA under contracts DTRA01-97-C-0153 and contract DTRA01-00-C-0115.

Report Overview

There have been three primary thrusts to our work under this contract. The common theme in all of our work is using seismic data to distinguish mining blasts from all other event types. We have used spectral characteristics of whole waveforms to discriminate ripple-fired explosions form instantaneous explosions and earthquakes. A primary objective was to apply an automated whole waveform time-frequency discriminant (ATFD) to large event populations in varied datasets to test transportability and robustness and to enhance the techqnique with more sophisticated processing. In section 1 of this report we give a brief summary of the results of our test of the ATFD algorithm to dissimilar, well separated, regional datasets with large populations of ripple and non-ripple-fired events. This section presents a summary of "A global test of a time-frequency small-event discriminant" written by the PI and published in 1998 in the Bulletin of the Seismological Society of America (v88, p973-988). This summary is brief. Although this work was completed under this contract, much of the analysis was completed under an earlier contract (F19628-95-K-0012). In section 2 we describe our use of seismic waveforms from 20 seconds period to 10 Hz to characterize well ground-truthed mine blasts in Wyoming. Included in this section is preliminary modeling of events in this region. Much of the research reviewed in section 2 resulted from collaborations with researchers at other institutions. This section is based on a paper entitled "Identification of Mining Blasts at Mid- to Far-regional Distances using Low-Frequency Seismic Signals" which was written by the PI, Brian Stump (SMU), Craig Pearson (LANL) and David Yang (LANL) and published in the Pure and Applied Physics journal in 2002 (v159, p831-863). Section 3 summarizes the main findings of a review article entitled Characterization of Mining Explosions at Regional Distances written by Brian Stump, the PI, Craig Pearson and Vindell Hsu and published in the Reviews of Geophysics *(40(4), 1011, doi:10.1029/1998RG000048, 2002)*. In this article we assess the state-of-the art in global monitoring of mining blast activity and explore avenues for further research needed in this area.

Section 1
A global test of a time-frequency small-event discriminant

1.1 Summary

In this section we summarize the key objective of this study, the method used to discriminate mining blasts from instantaneous explosions and eathquakes, the data sets, the results, conclusions and recommendations for further research. This work was started under an earlier contract (F19628-95-K-0012) but was completed under this contract. For this reason, we present a brief overview of this effort.

1.2 Objective

Mining activity is global, and given heightened interest in monitoring small seismic events (mb < 4.0) it is necessary that we develop the ability to routinely separate these events from all other event types. Although delay-firing is in use worldwide, exactly how mine blast shot grids are configured depends strongly on the mining objective and near-surface conditions. There is no standard mining event, even within most mining regions. For this reason, a key problem we must address is whether a single algorithm can be applied, without significant modification, in widely separated regions. It is this problem that we seek to address in this section.

1.3 The automated discriminant

It is well known that interference between seismic waves from delay-fired shots in a mine blast sequence

often yields enhancement of energy at certain, equispaced, frequencies (e.g. Baumgardt and Ziegler, 1988; Hedlin et al., 1989). Spectral scalloping that is not lost to attenuation during propagation to the receiver can be a diagnostic indicator of source multiplicity. It's existence in a spectrum can rule out the possibility the event was an instantaneous explosion or an earthquake provided alternate causes of modulations, such as resonance, can be ruled out. Hedlin et al (1989) observed that spectral modulations are commonly independant of time from the P-wave onset through the compressional and shear wave codas. Expanding a regional recording of a delay-fired mine blast into a 2-dimensional suite of spectra (spectragram or sonogram) will often reveal a diagnostic pattern of spectral scallops (Hedlin et al., 1989; Figure 1 of this report).

1.3 Multivariate discrimination analysis

The Automated Time-Frequency Discriminant (ATFD) is described fully in Hedlin et al. (1998) and only a brief review will be given here. The ATFD recognizes long duration modulations in the binary Short Time Fourier Transforms (STFTs; Hedlin et al., 1989; Daubechies, 1996; Hedlin et al. 1998) by applying three separate and simple tests. If 3-component data are available, the ATFD estimates independence from recording direction by cross-correlating the binary STFTs from separate components (vertical vs north-south, vertical vs east-west, north-south vs east-west). This gives 3 discriminantion parameters. The algorithm estimates the time-independence of the binary patterns by autocorrelation. The STFTs used in this study were calculated by sliding the window by 20% of its total length between each spectral estimate. This smooths the STFT in time and, as a result, the autocorrelation of each frequency at short lags is always high (Figure 2a). At long lags, the autocorrelation becomes independent of lag and is particularly low if the STFT lacks time-independence. The algorithm averages the autocorrelation at all long lags and at all frequencies. If 3-components are available, this test yields 3 additional discrimination parameters. Hedlin et al. (1990) developed a procedure to recognize time-independent patterns which are periodic in frequency. This technique utilizes a two-dimensional Fourier transform of the binary STFT, which reveals the dependence of the binary pattern on frequency and time. In view of its resemblance to the cepstrum (which identifies periodicity's in single spectra), and the fact that it is derived from onset and coda phases, it is referred to as the coda cepstrum (Hedlin et al., 1995). The algorithm takes the maximum of the time-independent portion of the cepstrum from each component (Figure 2b).

These operations are easily adapted to different kinds of deployments (*e.g.* single 3C station; 3C networks or arrays). Station-averaged values are used if multiple recordings are available. A vertical component deployment will yield just 2 discrimination parameters (autocorrelation and cepstral extreme). A 3-component deployment will yield a total of 9 variates.

These individual parameters are merged into a single discrimination score with the aid of multivariate statistics (Seber, 1984). Generally a linear discriminant function was used unless the dispersion matrices of the two event types were judged to be too dissimilar - in which case a quadratic is appropriate. In all cases it was assumed that the probability of each event type was equal and the discriminant decision was simply based on the sign of the discriminant function (as in Kim et al., 1993). In all cases standard tests were applied to ensure the validity of the statistical analysis.

1.4 The datasets

In this section we describe our first attempt to use one algorithm to discriminate mine blasts from other events in several widely separated regions. The "Automatic Time-Frequency Discriminant", otherwise

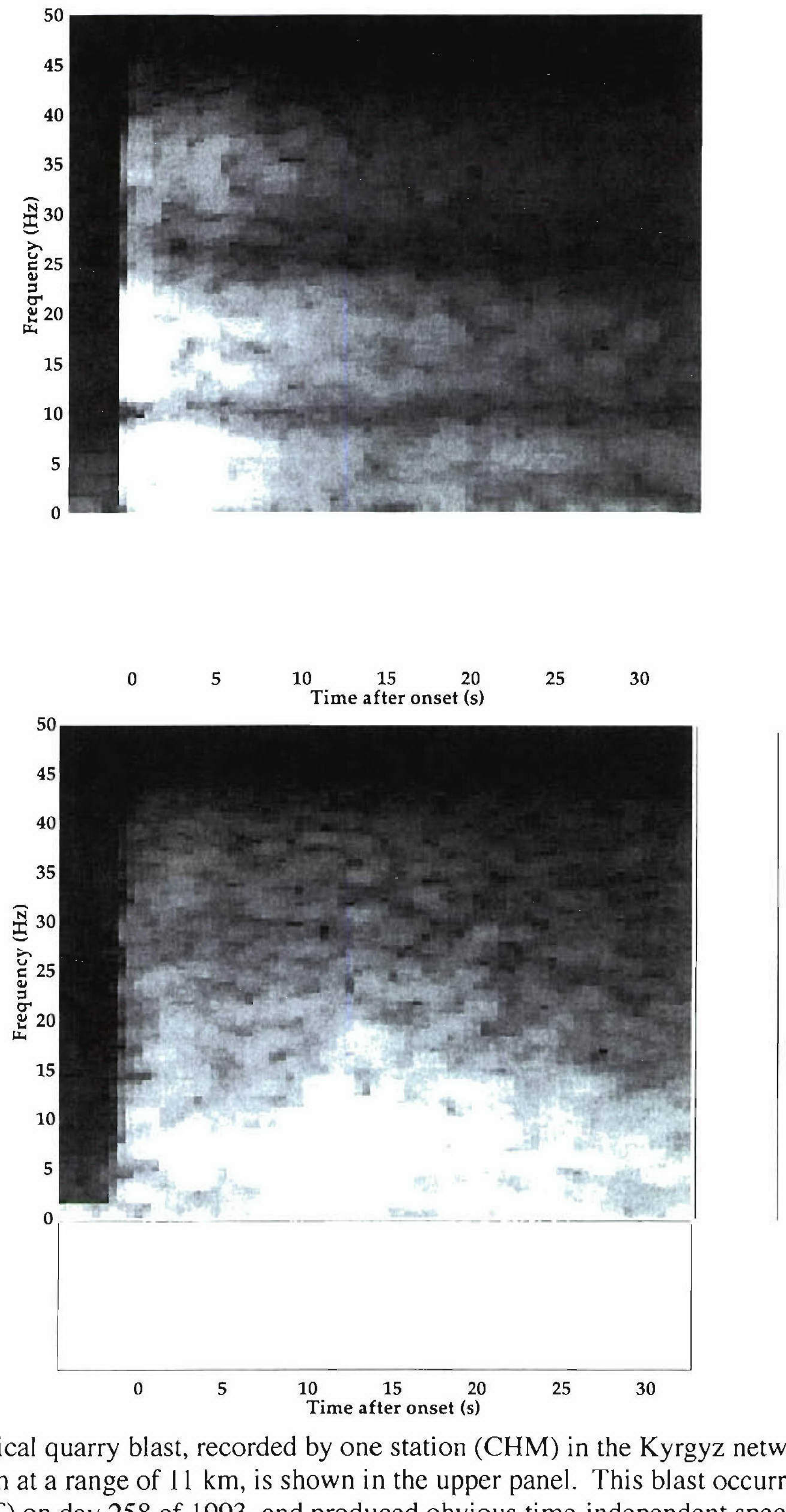


Figure 1. A typical quarry blast, recorded by one station (CHM) in the Kyrgyz network (KNET) station at a range of 11 km, is shown in the upper panel. This blast occurred at 9:04 AM (GMT) on day 258 of 1993, and produced obvious time-independent spectral modulations. A typical earthquake, recorded by a second KNET station (EKS) at a range of 78 km, is shown below. This event occurred at 42.55° N, 74.72° E at 4:12 AM (GMT) on day 250 of 1991..

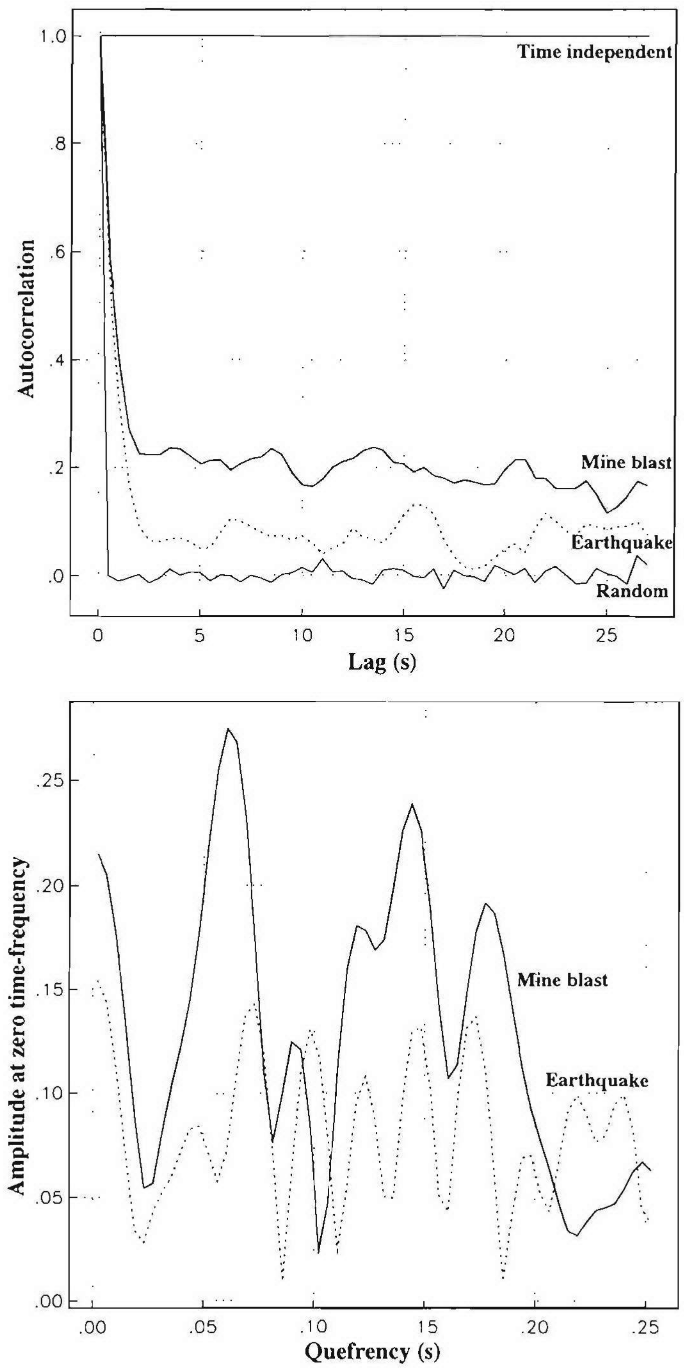


Figure. 2a and b. The upper panel shows the autocorrelations calculated for the two recordings displayed in Figure 1. Also plotted are the autocorrelations for a binary pattern which is perfectly random and one that is independent of time. The lower panel shows slices through the time-independent portions of two-dimensional "coda" cepstra computed from the vertical component recordings of the two events displayed in Figure 1. The quarry blast coda contains a significant amount of time independent energy below a quefrency of 0.06 s (solid curve). Much less time-independent energy is seen in the coda of the earthquake (dashed curve). These curves are normalized to a maximum value of 1 (which indicates a binary pattern which is perfectly independent of time and cyclic in frequency).

known as ATFD, was applied to data in five regions. The datasets were collected by the following deployments:

1) The sparse NRDC network in central Kazakhstan
2 and 3) Adense 3-component network in Kyrgyzstan (KNET) yielded 2 datasets
4) The NORESS small-aperture array in Norway
5) The GERESS small-aperture array in Germany
6) Single station recordings of mine blasts and earthquakes in the western US

1.5 The results from all datasets

The raw output of the ATFD for all 250 events considered in this study is organized into 3 panels which show the autocorrelation, cross-correlation and coda cepstrum extremes (Figure 3). In each panel, the 144 mine blasts are displayed on the left with the 3 single explosions and 103 earthquakes on the right. The background shading identifies the dataset. Since all datasets had at least one 3-component sensor, each event is described by 9 variates. Although there is some overlap, the delay-fired events are separated from the earthquakes and single explosions by each of the metrics. The networks (datasets 1 through 3) permit averaging over a broad region and give the most tightly clustered variates. The tight arrays (datasets 4 and 5) offer less spatial averaging, and the result is increased scatter of the variates. The greatest scatter exists in the single 3-component station results (dataset 6).

The discrimination scores for datasets 2 through 6 are presented in Figure 3. Scores for the first dataset have not been included since there were too few explosions (3) to permit a statistical evaluation. A visual inspection of the variates suggests that 2 of the 15 mining events would be difficult to discriminate from the single explosions using this approach. Of the 232 events in datasets 2 through 6, all but 6 were correctly identified. The misclassification probabilities ranged from 0.5% (5th dataset) to 3.5% (the 3rd). The ATFD appears to be robust, when given data recorded at near-regional (< 4°) range, and easily adapted to a wide range of deployments (from single stations to arrays and networks).

1.6 Discrimination Outliers

There are a number of processes which can inhibit the genesis of scallops at a delay-fired source. As pointed out by Stump & Reamer (1988) even though an intended shot-grid might be regular in time, shot time-scatter may be substantial enough to eliminate the constructive interference necessary to produce scallops. For reasons not yet fully understood, large portions of some mine blasts detonate simultaneously (Stump & Pearson, 1997). Energy released instantaneously couples very efficiently to seismic and might obscure modulations produced nearby by a delay-fired shot sequence (Smith, 1993; Mclaughlin et al., 1994). If significant variability between the basic wavefields exists (*e.g.* as discussed by Baumgardt, 1996) the time-stagger will still be in the recorded wavefield but perhaps difficult to extract since the wavefield will contain stagger without repetition. Further degradation might be due to non-linear near source effects (Minster & Day, 1986).

Propagation will further complicate the signals. An ever-present factor is attenuation, which will gradually erode any scallops produced by delay-firing. The high frequency scallops are most susceptible to attenuation and will be the first to fall below station noise. It is well known that resonance introduces repetition into wavefields and thus can lead to time-independant spectral scallolping (Hedlin et al., 1989).

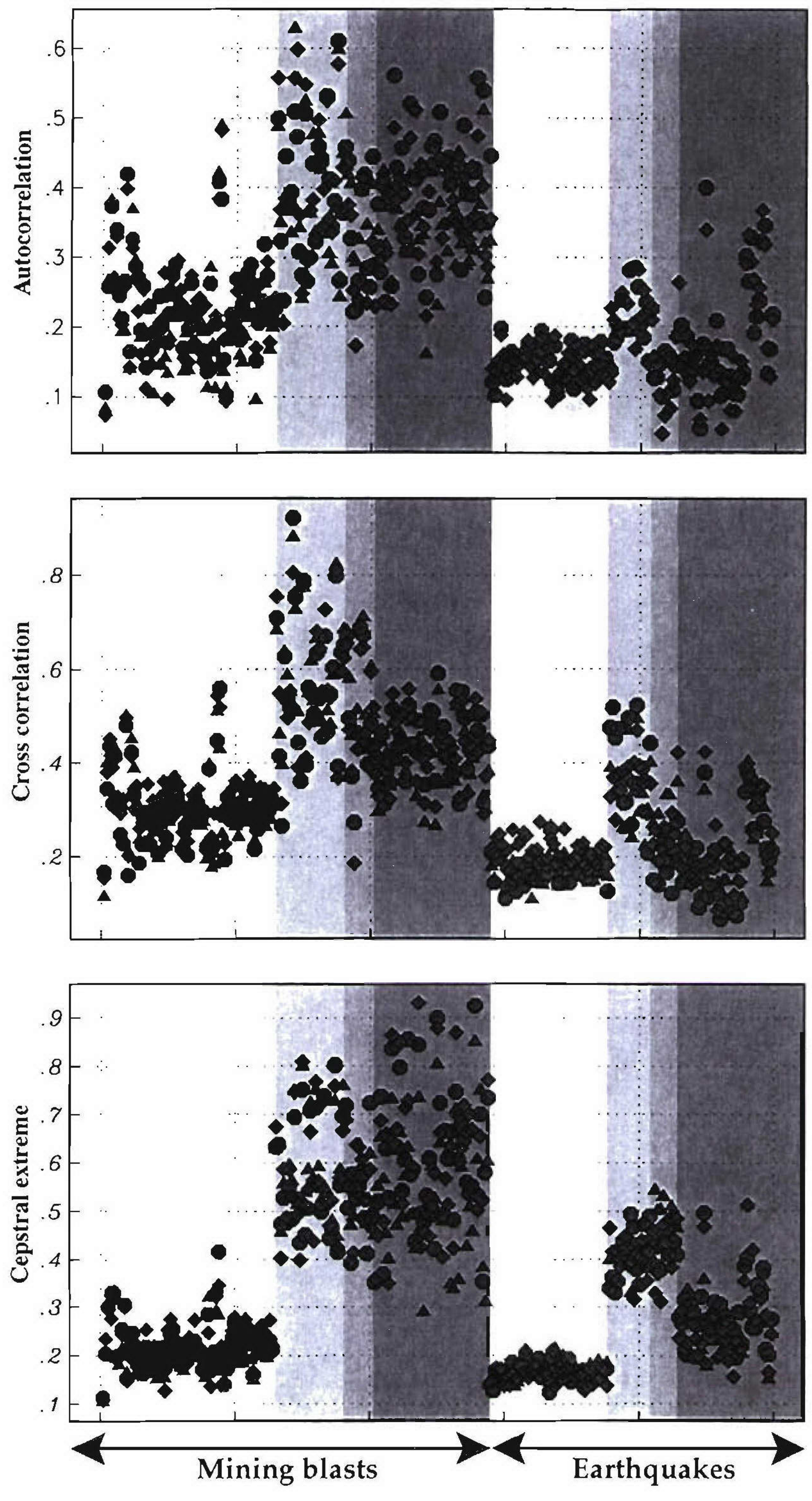


Figure. 3. Raw output from the ATFD for all 250 events considered in this study. Events believed to be mining blasts are located on the left; the single explosions (dataset 1) and earthquakes are located on the right. The results from datasets 1 through 6 are arranged from left to right with background shading indicating the dataset. The three discrimination methods (autocorrelation, cross-correlation and coda-cepstra extremes) are shown from top to bottom.

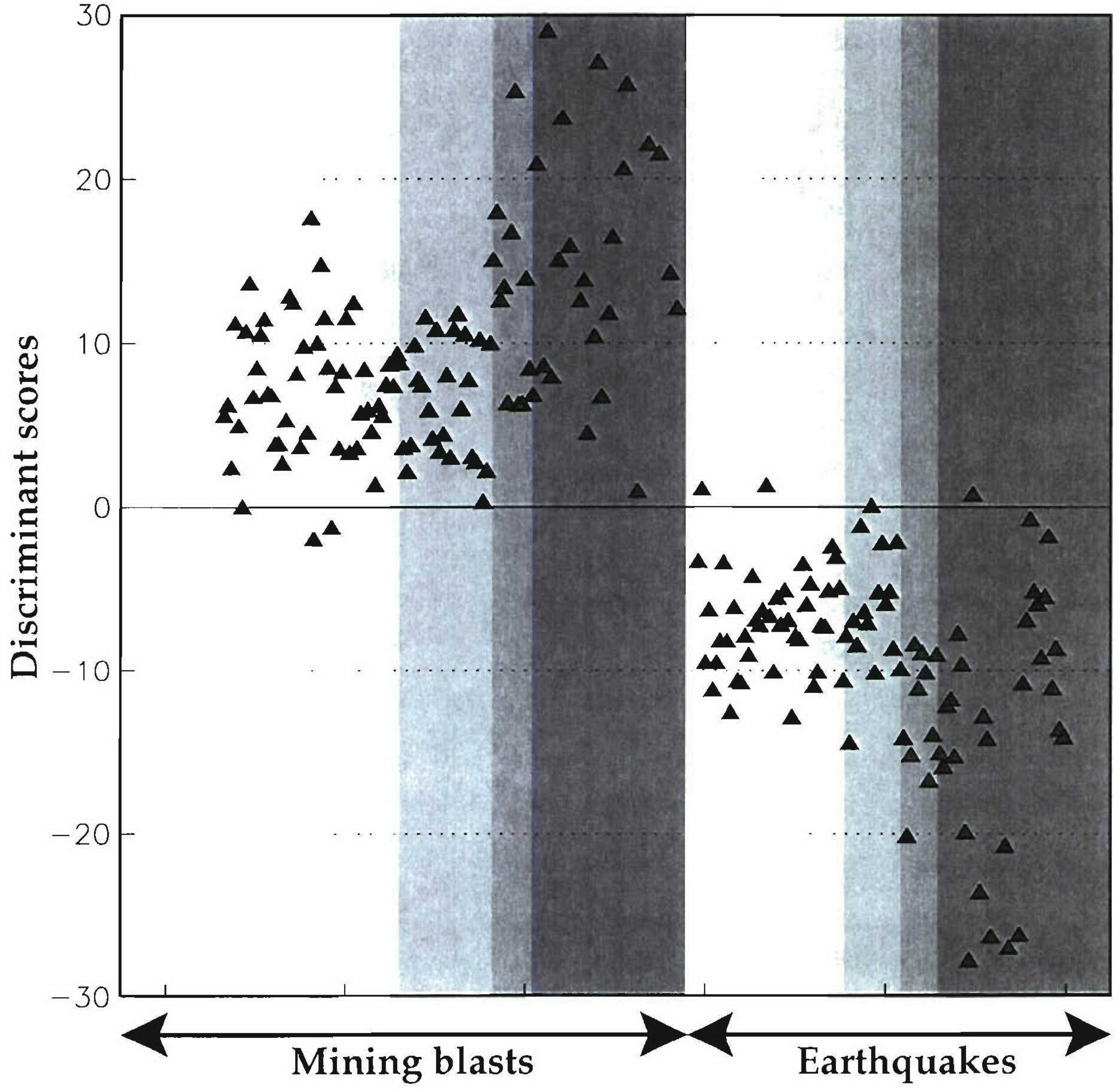


Figure 4. Discriminant scores from datasets 2 through 6. Scores for the first dataset have not been included since there were too few explosions (3) to permit a statistical evaluation. Linear discrminant functions were used for the second through fifth datasets; the sixth required a quadratic. The raw parameters suggest that 2 of the 15 mine blasts in the NRDC dataset would be misidentified. Of the 232 events in the other datasets, all but 6 were correctly identified. The scatter increases as averaging becomes less effective. It is most severe in the 6th dataset which was collected by a single station.

1.7 Concluding Remarks

This global study indicates that high-frequency spectral modulations are a common seismic by-product of delay-fired mine blasts and can be sensed routinely within 4° of the source. A time-frequency discriminant which seeks these spectral features will distinguish most mining blasts from natural events, regardless of tectonic setting, local mining techniques and the style of seismic deployment. Tests using a dense central-Asian network and European arrays show that averaging increases stability of the output of the algorithm, however the single station results from Nevada indicate that, at least in some regions, this is not essential. In spite of this success, the few discriminant outliers are troubling as they point to factors which can confuse any method that relies on spectral modulations.

One of the underlying conclusions of this study is that discrimination should not rely on any single technique. Because of intrinsic source effects such as shot scatter, waveform decorrelation and non-linear superposition, spectral modulations are not produced by all delay-fired events. If they are present at the source they will eventually be lost to attenuation. Non-delay-fired events will sometimes be recorded with spectral modulations either because of propagation resonance (Hedlin et al., 1989) or station noise. Resonance that occurs near the source is problematic. If the two-way travel time is comparable to inter-shot or inter-row delay times commonly used in mining (30 to 200 msec), the potential for confusion is acute. For these reasons, the time-frequency method must be paired with other techniques for the most robust discrimination. The discriminant suite will have to be tailored to the region of interest. For example, in regions like central Kazakhstan, propagation Q is high and the time-frequency approach should provide important input to the source characterization. In other areas, for example the western USA, high-frequency spectral features will not survive to mid-regional distances. The spectral modulations in this example suggest a repetition time of 100 msec; which is within the range of normal delay-firing shooting. The waveform, however, is not explosion-like and would easily be recognized as such by any one of a number of time-domain discriminants (e.g. P/Lg).

The need for a suite of discriminants is increased by the occasional, extreme, source effects. A mine blast which includes a sympathetic detonation can be regarded as a double event. This kind of event is troubling to the mining community because the instantaneous detonation reduces efficiency of the shot sequence. Much of the energy in the sympathetic detonation couples to seismic and boosts the 'magnitude of the event. This poses a concern for the monitoring community as these seismically bright events will trigger the IMS network and might be difficult to properly characterize. The time-frequency method alone might not be able to distinguish an uncomplicated mine blast from one which includes a large single explosion as spectral modulations might still be visible (Smith, 1993; McLaughlin et al., 1994). A suite of techniques that consider other signal qualities (such as m_b) might be effective at sensing a large simultaneous detonation although the question of whether the single explosion was nuclear or chemical might require a more thorough inspection. A credible evasion scenario being considered is the "hide-in-quarry-blast" (Barker et al., 1990) in which a nuclear test is detonated within a mining delay-fired shot sequence.

To test the transportability of the ATFD, the calculation parameters were fixed at the start of the experiment and not optimized for any dataset. For example, the filters, which are used to convert spectral STFTs to binary form, are narrow (span 4.4 and 2.0 Hz) and are designed for modulations which repeat every 5 to 10 Hz. Fine tuning parameters, such as these filters, for use in a specific region should decrease the misclassification probabilities. A more advanced discriminant might consider more than just the presence or absence of modulations but compare any found with those known to be produced by local mines. This anomaly suggests that the quefrency should be considered by the discriminant. In this

case, the quefrency of the energy in the typical mine blasts is 80 to 100 msec. The outlier's peak energy lies at 400 msec.

Some regions of great interest will be monitored at near-regional range and so there is a need for high frequency discriminants. Because of the sparse nature of the global seismic network, however, most monitoring will be conducted at greater distances. There is a pressing need for discriminants which use low-frequency signals to sense source effects from a greater range. Although millisecond delay-fired mine blasts will produce diagnostic spectral peaks at high frequency, because of interference between shots, there are numerous observations of spectral features well below 10 Hz which have not been attributed directly to the delays, but to source finiteness (*e.g.* Gitterman & van Eck, 1993; Hedlin, 1997). These observations are particularly encouraging because they hold the promise of characterization of millesecond delay-fired events in sparsely instrumented regions.

At first sight, an apparent drawback of the STFT is that it offers time-frequency resolution that is invariant with frequency. This is at odds with the physics of the signal since high-frequency transients will be short lived relative to those at lower frequencies. Expansion techniques that use wavelets which traverse the timeseries by translating in time and scaling in frequency offer flexible time- and frequency-resolution (Daubechies, 1990). Although the fine details of the time-frequency structure are interesting, we are seeking a source effect which systematically enriches certain frequency bands at the expense of others. These effects can be long lived regardless of their frequency. Wavelet expansions have not been adopted for this reason, and because they are time consuming. The automated algorithm prizes computational speed.

1.8 Future research objectives

By necessity, most datasets used in this study (#'s 2 through 6) included recordings of mine blasts and earthquakes. Earthquakes should not yield seismic signals with time- or component- independent spectra and thus have been used as proxies for single explosions. This study has assessed the effectiveness of a high-frequency spectral discriminant within 4° of the source. To test transportability, the discriminant has been tested on a collection of widely dispersed datasets, but at a cost. With the exception of the 6th dataset (collected by LLNL) thorough ground truth data is lacking and so only limited understanding of the causes of outliers has been possible. There is a pressing need for mid- to far-regional recordings of well documented mine blasts and calibration explosions. Toward this end, UCSD has recently conducted a regional calibration experiment in Wyoming with Brian Stump (SMU), Craig Pearson (LANL) and Vindell Hsu (AFTAC). This experiment produced recordings of single (calibration) explosions and mine blasts occurring in the Black Thunder coal mine. Ground truth data on these events has been collected by LANL/SMU with acoustic, video and seismic equipment in the mine, as well as mine records. Section 2 of this report describes our use of seismic waves from 20 seconds to 10 Hz which are unique to the mine blasts and can be used at greater range than the signals considered in this section. We will examine why some millesecond delay-fired blasts do not yield high-frequency modulations and would be misidentified by the ATFD. Modeling will be used to give our observations a firm physical grounding.

Section 2

Identification of Mining Blasts at Mid- to Far-regional Distances Using Low-Frequency Seismic Signals

2.1 Summary

This section is based on a paper entitled "Identification of Mining Blasts at Mid- to Far-regional Distances using Low-Frequency Seismic Signals" which was written by the PI, Brian Stump (SMU), Craig Pearson (LANL) and David Yang (LANL) and published in the Pure and Applied Physics journal in 2002 (v159, p831-863). The analysis was funded under this contract however funds to conduct the field experiment were provided by LANL (under contracts 1973USML6-8F and F5310-0017-8F).

This section reports results from two recent monitoring experiments in Wyoming. Broadband seismic recordings of kiloton class delay-fired cast blasts and instantaneous calibration shots in the Black Thunder coal mine were made at four azimuths at ranges from 1 to 2°. The primary focus of this experiment was to observe and to explain low-frequency signals that can be seen at all azimuths and should routinely propagate above noise to mid-regional distances where most events will be recorded by International Monitoring System (IMS) stations.

The recordings clearly demonstrate that large millisecond delay-fired cast blasts routinely produce seismic signals that have significant spectral modulations below 10 Hz. These modulations are independent of time, the azimuth from the source and the orientation of the sensor. Low-frequency modulations below 5 Hz are seen beyond 9°. The modulations are not due to resonance as they are not produced by the calibration shots. Linear elastic modeling of the blasts that is guided by mine-blast reports fails to reproduce the fine detail of these modulations but clearly indicates that the enhanced "spectral roughness" is due to long interrow delays and source finiteness. The mismatch between the data and the synthetics is likely due to source processes, such as nonlinear interactions between shots, that are poorly understood and to other effects, such as variations of shot time and yield from planned values, that are known to be omnipresent but cannot be described accurately. A variant of the Automated Time-Frequency Discriminant (HEDLIN, 1998), which uses low-frequency spectral modulations, effectively separates these events from the calibration shots.

The experiment also provided evidence that kiloton class cast blasts consistently yield energetic 2-10 second surface waves. The surface waves are strongly dependent on azimuth but are seen beyond 9°. Physical modeling of these events indicates that the surface waves are due mainly to the extended source duration and to a lesser extent to the slap-down of spalled material. The directionality is largely a path effect. A discriminant that is based on the partitioning of energy between surface and body waves routinely separates these events from the calibration shots.

The Powder River Basin has essentially no natural seismic activity. How these mining events compare to earthquake observations remains to be determined.

2.2 Introduction

The recent Comprehensive Nuclear Test-Ban-Treaty (CTBT) is unlike any earlier test ban accord, such as the Threshold Test Ban Treaty (TTBT) which prohibits tests above 150 kilotons, as it bans nuclear explosions of any yield. The exclusive nature of this treaty and the fact that a 1 kiloton contained explosion in hard rock is well above magnitude 4 motivates interest in the accurate characterization of small (mb < 4.0) seismic events (Murphy, 1995). Detonating a nuclear explosion in a cavity can further reduce the magnitude of the seismic waves (*U.S. CONGRESS, OTA REPORT, 1988*). Interest in small events has increased both the numbers of events that must be considered and the types. It is estimated that, globally, 21,000 events with m_b above 3.5 occur per year (*U.S. CONGRESS OTA REPORT; P 78*). Some of

these small events will not be associated with natural seismic activity but are due to commercial blasting which occurs globally. The blasting technique favored worldwide is delay firing (LANGEFORS AND KIHLSTROM, 1978) in which a number of charges are arranged in a spatial grid and detonated in sequence. This technique is favored as it yields efficient fracturing of rock while minimizing damaging seismic and acoustic signals in areas proximal to the mine. Commercial blasting is common but usage varies widely (*LEITH, 1994*). *KHALTURIN ET AL. (1997)* surveyed over 30 regions worldwide and found that several hundred industrial blasts each year have a magnitude greater than 3.5. Large blasts, often associated with construction, were relatively common in the Former Soviet Union and in China however the current blasting practice is not yet well known (Bill Leith - personal communication). In Wyoming, very large (> 1 kt) surface coal mine blasts are common. The Black Thunder coal mine, one of several mines in the Powder River Basin in NE Wyoming, typically detonates 1 to 2 blasts of this magnitude each month (*PEARSON ET AL., 1995; STUMP, 1995*) with a few in the magnitude range of 3.5 to above 4.0.

The Reviewed Event Bulletin (REB), published by the prototype International Data Centre (PIDC), indicates that large mining explosions are commonly detected by IMS seismic stations at all regional distances; some are seen teleseismically. Although there has been very promising progress in identifying mine blasts using correlation techniques (Harris, 1991, Israelson, 1991, Riviere-Barbier and Grant, 1993), significant changes in how mine blasts are detonated at an individual mine are known to occur (Martin et al., 1997). This gives us the impetus for exploring other, complimentary, methods. Large mining events are problematic not just because these events will trigger the IMS, but these large, controlled, explosions offer a means to obscure nuclear tests. The "hide-in-quarry blast" evasion scenario (BARKER ET AL., 1990;94; RICHARDS AND ZAVALES, 1990; SMITH, 1993), in which a nuclear test is co-located with a mining blast, might be troubling because blasting anomalies, in which a large part of a mining explosion shot grid detonates simultaneously, are not uncommon (MARTIN ET AL., 1997). A nuclear test co-located with an industrial explosion might be entirely hidden or mistaken for a detonation anomaly.

The CTBT calls for an International Monitoring System (IMS) which will comprise four networks of sensors (seismic, infrasound, radionuclide and hydroacoustic). The seismic network will consist of 50 primary stations and over 100 secondary stations (Figure 5). This network will place a station within local distance (1°) of 2% of the Earth's landmass. The near-regional (within 5°) coverage will be 34%. The mid-regional coverage (within 15° of the source) is nearly complete at 89% (Figure 6). If multiple recordings are required for accurate source characterization, the coverage is more limited. Just 22% of the Earth's landmass is within 10° of 3 stations; 74% is within 20°. Some prominent mining regions (*e.g.* the Kuzbass/Abakan mining region in Russia near the IMS station ZAL) will be monitored at near-regional range (Figure 6) and a full suite of high and low frequency characterization techniques can be brought to bear on suspicious events (STUMP ET AL., 1999a). In many regions, however, monitoring of man-made and natural seismic activity will rely on recordings made at mid- to far-regional range. Events in these regions will require a more limited set of seismic discriminants: those that operate at low frequencies. Although millisecond delay-fired industrial explosions will produce diagnostic spectral peaks at high frequency, because of interference between shots, the industry standard intershot time delay is 35 msec and the resulting spectral peak is at ~ 30 Hz (the inverse of the intershot time delay). As the standard sampling rate for IMS stations is 40 samples/sec (sps), this energy will lie beyond the Nyquist frequency of most recordings that will be made under the CTBT.

Quantitative detection capability of the IMS involves many factors, including spatial decay rates, event size, noise levels, instrument type (e.g. array, single station), and phase (e.g. *P* and *S*). There have been many studies quantifying these into the detection capability of the IMS (e.g. Wuster et al, 2000). The

analysis in this case is to emphasize the distance range at which observations of mining explosions are most likely to be made.

It is apparent that large blasts emit seismic energy which can be used for source characterization from local to far-regional distances. Spectral modulations below 10 Hz have been observed by several groups (*incl.* BAUMGARDT AND ZIEGLER, 1988) and are usually attributed to long intershot, or interrow, delays. GITTERMAN AND VAN ECK (1993) attributed a low frequency spectral notch in recordings of mine blasts to source finiteness. Unusual time-domain characteristics also have been observed. ANANDAKRISHNAN ET AL. (1997) and STUMP AND PEARSON (1997) observed significant surface waves caused by cast explosions in Wyoming. GITTERMAN ET AL. (1997) observed surface waves in recordings of quarry blasts in Israel. ANANDAKRISHNAN ET AL. (1997) modeled the Wyoming blasts and concluded that the surface waves are due to long source duration and significant spall, including material cast into the pit.

This section presents further evidence for significant seismic signals produced by large mining blasts and not by instantaneous explosions. The section presents evidence for spectral modulations below 10 Hz produced by documented ("ground truthed") cast blasts in Wyoming. Low-frequency modulations, below 5 Hz, are seen at an IMS station at a range of 9°. The section identifies observations of significant surface waves also produced just by these events. Source modeling is used to understand these observations and to gauge the sensitivity of these signals to changes in blasting parameters at the source. We assess the usefulness of these signals, and low-frequency spectral modulations, for characterizing mining explosions using the IMS.

2.3 Regional Monitoring Experiments in Wyoming

To investigate low-frequency seismic signals produced by large mining blasts, researchers from the University of California, San Diego (UCSD), in collaboration with researchers from the Los Alamos National Laboratory (LANL), Southern Methodist University (SMU) and the Air Force Technical

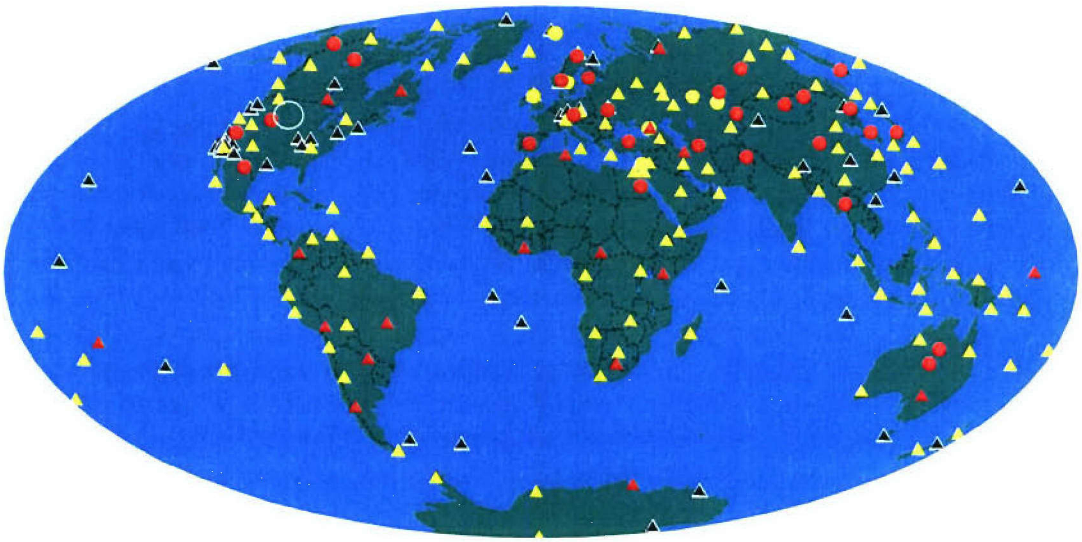


Figure 5. Distribution of current and proposed primary (red) and auxiliary (yellow) IMS seismic stations. Array sites and three component stations are represented as circles and triangles respectively. Additional stations (in black) are in the IRIS GSN. A regional network considered in this study was deployed in Wyoming and is represented by the oval.

IMS primary and auxiliary seismic net coverage

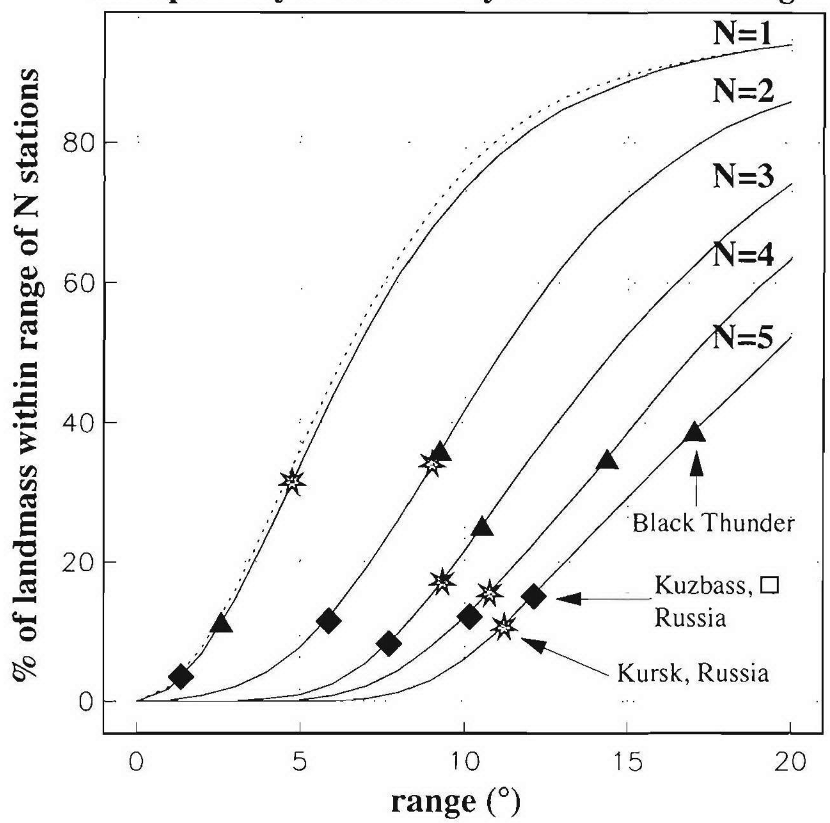


Figure 6. Coverage of the Earth's landmass permitted by the current and proposed IMS primary and secondary seismic networks is indicated by the solid curves. Single station coverage (N=1) is nearly complete within 10° of the source. If multiple recordings of an event are required for adequate source characterization (N>1), most of the observations will be made at mid- to far-regional or teleseismic range. Coverage of 3 prominent mining regions is indicated by shaded symbols. Krasnogorsky, the main Kuzbass mine in Russia, at 53.6°N, 87.8°E; Black Thunder in Wyoming at 43.7°N, 105.25°W and Kursk, Russia at 51.8°N, 36.5°E are represented by diamonds, triangles and stars, respectively. These mining regions will be monitored somewhat more closely than the average. For example, 3 stations are within 8° of the Kuzbass mine. Just 8% of the Earth's landmass has better coverage. The dashed curve is coverage given by the IMS networks (current and proposed) and existing stations in the GSN. Many stations in the GSN that are not already in the IMS are located on oceanic islands and so the improvement is limited.

Applications Center (AFTAC), conducted two regional monitoring experiments in Wyoming in 1996 and 1997. Five broadband 3-component seismic stations (STS-2's; flat response from 0.0083 to 40 Hz) were deployed within near-regional range of the Black Thunder mine (Figure 7). Four of the sensors were deployed in a ring at 200 km range to study the azimuthal dependence of the seismic signals. The

fifth station was deployed (in 1996) at a range of 100 km to the north of the mine along the azimuth to station CUST to allow examination of the range dependence. A 3-element, 100 m aperture infrasound array was deployed at station MNTA (Figure 7). The temporary deployments complemented permanent, nearby, deployments at PDAR, RSSD and more distant stations in the IMS and the IRIS Global Seismographic Network (GSN).

The seismic activity in this region is almost entirely man-made and is concentrated in the Powder River Basin coal mining trend (Figure 7). Two types of blasting are most common in this trend. The largest blasts are used to cast overburden to the side to expose the coal seam (MARTIN AND KING, 1995). Smaller shots are used to fracture the coal seam to facilitate recovery (ATLAS POWDER COMPANY, 1987). Event clusters correlate well with known mine locations (Figure 7). The events of greatest interest were the large cast blasts and calibration shots, located in the Black Thunder coal mine (PEARSON ET AL., 1995; STUMP, 1995), as these were closely monitored with video and acoustic equipment by the LANL team and were carefully documented by personnel at the mine. During the two experiments, 4 large cast blasts were detonated at Black Thunder (Figure 8; Table 1). These blasts ranged from 2.5 million pounds (Aug 1, 1996) to 7 million pounds (August 14, 1997) and were used to move overburden. Three of four blasts occurred in the south pit of Black Thunder where overburden is cast to the north. Typical cast blasts include several (typically ~ 7) rows of shots. Intershot time spacing is 35 msec, rows are spaced by 200 to 300 msec. For reasons as yet not fully understood, one cast blast (Aug 1, 1996) detonated, in part, nearly simultaneously. Six calibration shots (ranging from 5000 to 16000 pounds) were detonated in the mine in 1997 (Figure 8; Table 2). The first four calibration shots (yields 5000 to 5500 pounds) consisted of a single cylindrical borehole. The fifth and sixth calibration shots (yields 12,000 and 16,000 pounds) consisted of 3 and 4 boreholes respectively. The boreholes in the larger shots were spaced 20 to 30 m apart and detonated simultaneously. In the discussion that follows, we consider the time and frequency domain characteristics of all large Black Thunder events that occurred during the two experiments. However we will focus on two events; the 4.5 million pound cast blast that occurred on July 19, 1996 and the 16,000 pound calibration shot.

2.4 Observations of Low-Frequency Seismic Signals from Mining Blasts

2.4.1 Time domain energy partitioning. Amplitudes of body waves produced by the 4.5 million pound July 19 cast blast are comparable to those produced by the 16,000 pound calibration shot (Figure 9). This is expected as the July 19 blast yield is spread out over 620 shots which were arranged in 7 rows and ripple-fired over ~ 4.8 s. Each shot hole was decked - that is two explosive charges were detonated with a small delay in each hole. Although the two events produced similar body waves, just the cast shot produced significant surface waves (Figure 9). Unfiltered recordings of the July 19 blast (Figure 10) show the progression from high frequency body waves to low frequency surface waves at four azimuths. The surface wave amplitudes exhibit a clear dependence on azimuth. Figure 11 indicates that although the low-frequency waveforms are highly dependent on azimuth, these signals do not seem to depend strongly on the fine details of the source if the blasts are in the same pit.

ANANDAKRISHNAN ET AL. (1997) and STUMP AND PEARSON (1997) have published PDAR recordings of significant 4 to 12 second surface waves which are produced by cast blasts in Wyoming. ANANDAKRISHNAN ET AL. (1997) used linear source modeling to argue that the surface waves are the result of the long source duration and spall impacts. The 1996 and 1997 regional experiments indicate that these surface waves are routinely produced by the cast explosions and are readily detected at near-regional range.

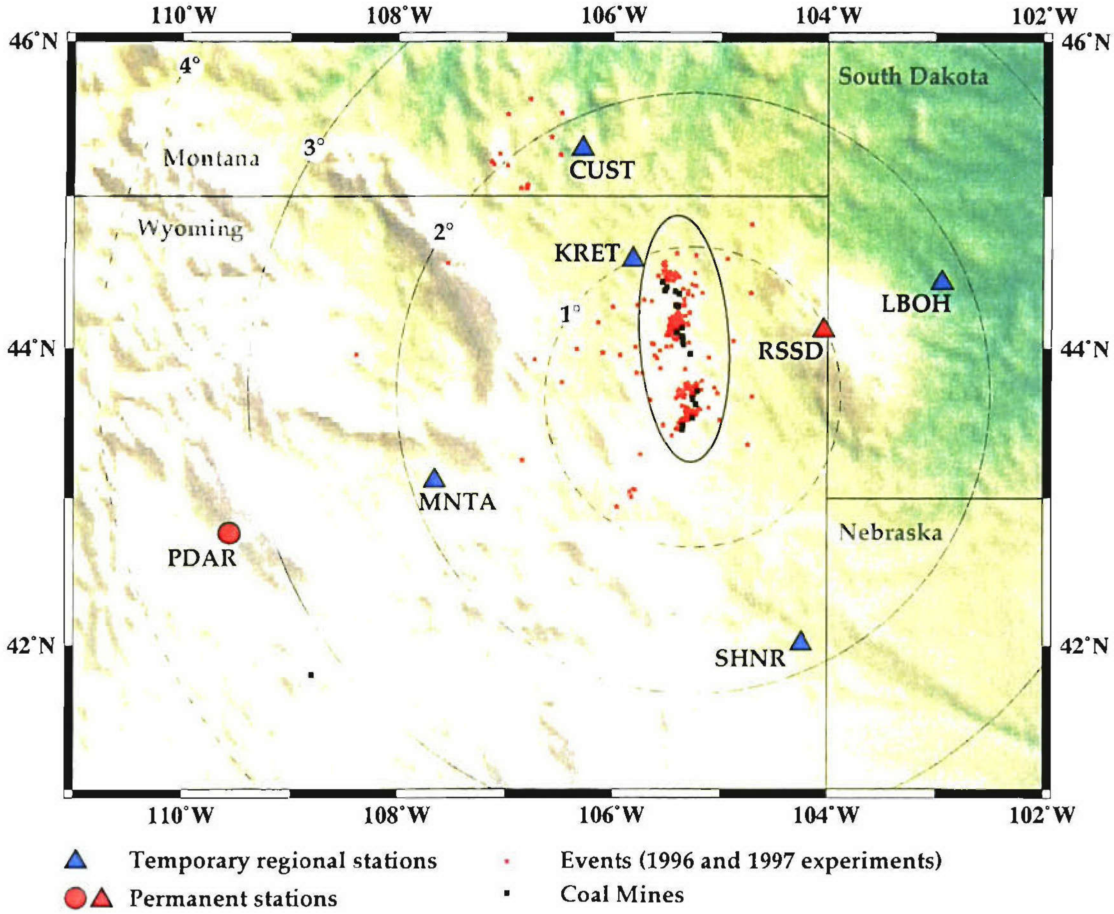


Figure 7. Two regional experiments were conducted in Wyoming by LANL, SMU, AFTAC and UCSD in 1996 and '97. Four broadband seismic stations (3-component STS2's) were deployed in a ring surrounding the Powder River Basin (PRB) at a range of 200 km from the Black Thunder coal mine. A fifth station (KRET) was deployed at a range of 100 km. Permanent seismic stations are located at PDAR and RSSD. Infrasound sensors were deployed at MNTA. Mining explosions detected by the temporary seismic stations during 49 days in 1996 and 1997 are plotted and correlate well with known mines. The slight northward bias is likely due to the 1D model. The oval indicates approximate limits of the PRB.

In Figure 9, peak amplitudes in two pass bands (1 to 10 Hz; centered at *P* onset and 2 to 10 seconds centered on the surface wave) are estimated from noise-corrected envelopes of recordings made by the stations in the 200 km ring (Figure 7). The cast blasts and calibration explosions are easily separated despite the strong dependence of the peak surface wave amplitudes on azimuth. Although small calibration shots yield *P* waves that are comparable in strength to those produced by the much larger, but not concentrated, cast blasts, just the latter events produce significant surface waves. As indicated in this figure, the calibration shots yielded no surface wave energy above noise. The lone outlier, among the population of cast blasts, is the Aug 1, 1996 event. A significant simultaneous detonation, which occurred within this blast, significantly boosted peak *P* wave amplitudes. The network average surface wave amplitudes are almost identical, despite the significant differences in how these blasts were deto-

The Black Thunder Mine

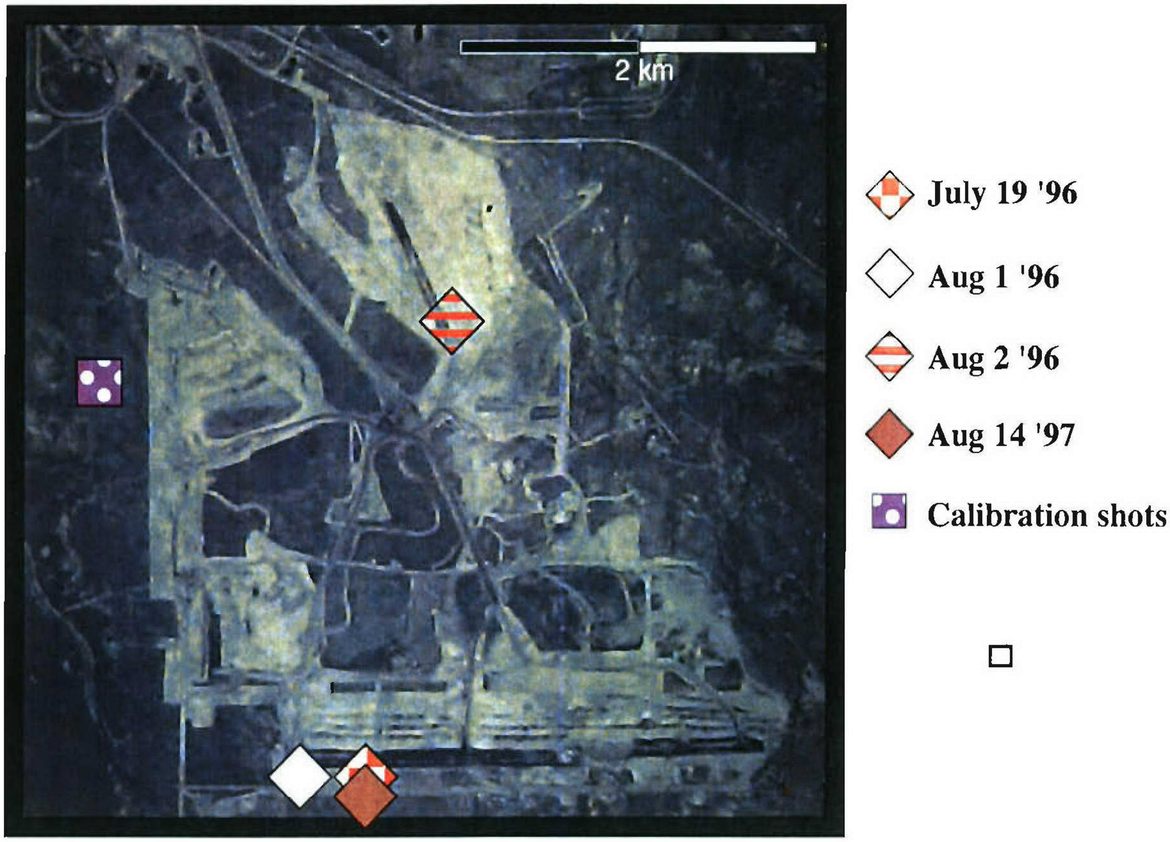


Figure 8. A satellite photo of the Black Thunder Coal mine in Wyoming. The symbols give approximate locations of the major events considered in this paper. The 1996 and 1997 experiments produced recordings of 4 significant cast blasts in the Black Thunder coal mine. The July 19, Aug 1.96 and Aug 14.97 blasts occurred at the west end of the south pit. The west end of the Aug 1 blast is believed to have detonated simultaneously. In the July 19, Aug 1, Aug 2 (all 1996) and Aug 14 (1997) cast blasts 4.5, 2.5, 2.8 and 7.0 million pounds of ANFO were detonated. The two largest calibration tests involved 12,000 and 16,000 pounds of ANFO.

nated. Despite the boosted *P* wave amplitudes observed in the Aug 1, 1996 recordings, the amplitude ratio comparing surface waves to body waves still separates this event from the single shots.

2.4.2 Frequency Domain Modulations Previous studies (*incl.* STUMP AND PEARSON, 1997) have shown that the large cast explosions in Wyoming do not yield obvious spectral modulations above 10 Hz. The intershot delays of 35 msec concentrate energy at multiples of 29 Hz (1/0.035 s). Close-in data show a spectral increase that corresponds to the 35 ms delays although the peak is relatively broad, reflective of the different spatial locations of the individual charges and possibly variance in their individual detonation time. Rapid attenuation in this area is an additional cause of the faintness of the high-frequency modulations. These explosions do, however, produce significant modulations below 10 Hz. Spectral estimates taken from recordings of the July 19, 1996 cast blast made by the 5 station regional network are shown in Figures 13 and 14. These spectra exhibit only a modest dependence on time, the

Table 1. Significant blasts at Black Thunder during the period of our study.

Date	Pit/Firing Direction	# Rows/# Holes	Intershot/Interrow Delays (ms)	Total Explosive yield (pounds)
July 19, 1996	South/West	7/620 (Decked)	35/200-275	4,549,366
Aug 1, 1996	South/West	7/341	35/200-275	2,460,730
Aug 2, 1996	NE/South	7/422	35/200-275	2,784,540
Aug 14, 1997	South/West	7/702	35/200-400	5,958,010

TABLE 2. A summary of the calibration shots at Black Thunder in 1997.

Date	Yield (pounds)
Aug 14, 1997	~ 5500
Aug 14, 1997	~ 5500
Aug 14, 1997	~ 5500
Aug 14, 1997	~ 6000
Aug 15, 1997	~ 12000
Aug 15, 1997	~ 16000

recording direction, and the azimuth from the mine. No organized spectral modulations are seen in the recordings of any of the calibration shots. In this figure we display spectra from the 16,000 pound shot (dashed curves). As will be seen later, the low frequency modulations below 5 Hz are seen out to 9°.

2.5 Waveform Synthesis

To give these basic observations a physical basis, we turn to synthetics. The synthesis of extraordinarily complex mining explosions has become relatively easy given the early work of BARKER ET AL. (1990, 1993) and MCLAUGHLIN ET AL. (1994) and recent work by X. Yang who has modified the linear elastic algorithm of ANANDAKRISHNAN ET AL. (1997) and packaged it into an interactive MATLAB package (MineSeis; YANG, 1998). The algorithm assumes the linear superposition of signals from identical single-shot sources composed of isotropic and spall components. Both shooting delays and location differences among individual shots are taken into account in calculating delays of the superposition, although the Green's functions are assumed to change slowly so that a common Green's function is used for all the single shots. We used a reflectivity method to calculate the Green's functions. A 1-dimensional velocity model was used (PRODEHL, 1979; ANANDAKRISHNAN ET AL., 1997).

To model the July 19 cast blast we used a blast report issued by the Black Thunder Mine. The blast consisted of 7 rows and a total of 620 decked shots with a total yield of 4.5 million pounds (Table 1). In a decked shot, more than one charge is detonated in the same hole. In this event, each hole contained two charges separated by 50 to 200 msec. Although the number of shots in each row varied from 85 to 93, for simplicity we assumed each row had 89 shots and that each decked shot had a total yield of 0.0033 kt. We assumed that all rows were spaced by 9.1 m and that all adjacent shots in the same row were 10.4 m apart. Intershot delays were 35 msec, interrow delays ranged from 200 to 275 msec. SOBEL (1978) estimated that 9.6×10^9 kg of material is spalled by each kt detonated. In our experiment, each decked shot had a total yield of 0.0033 kt and thus the Sobel relation gives ~31 kt of spalled material. For the July 19 Black Thunder event we found this figure yielded surface waves that were more ener-

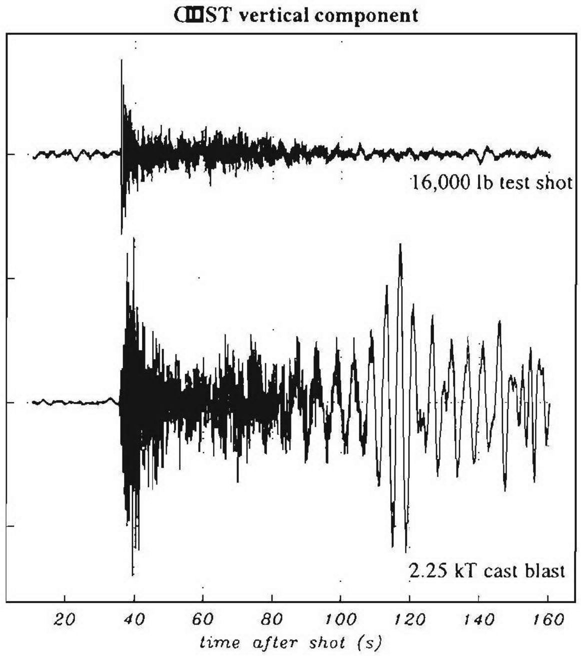


Figure 9. Unfiltered vertical component recordings of a 16000 pound calibration shot (top) and a 4.5 million pound cast shot made at CUST. Both recordings are plotted at the same scale. The station was located 200 km to the north of the events (Figure 7) which occurred in the Black Thunder coal mine. The tiny calibration shot rivals the immense cast shot as a source of *P* waves but is an insignificant source of surface waves. The dissimilarity of unfiltered vertical component recordings made at CUST is consistent with previous findings (*Kim et al., 1994; Anandakrishnan et al., 1997*) and suggests that a regional variant of the Ms:m_b discriminant could be effective for separating large mine blasts from instantaneous explosions.

getic than those that were recorded and so we reduced the spall figure to 20 kt. As will be discussed later, this discrepancy can be due to the incomplete conversion of spalled kinetic energy into seismic or to inadequacy of the velocity model. We assumed that the spalled material was cast at an angle 10° above the horizontal and fell 20 m.

Some vertical component synthetics are shown in Figure 15. This figure illustrates the relatively energetic surface waves that can be expected from cast blasts. The 16,000 pound point synthetic source, modeled as an isotropic source, produces a weak surface wave. The figure also illustrates the slow attenuation of the surface wave produced by the synthetic cast blast.

The peak amplitudes of the point source and the July 19, 1996 cast blast synthetics at a range of 200 km have been calculated for the 4 outer stations in the regional network (Figure 7) and are displayed in Figure 9 with the observed amplitudes from the recorded events. Despite the assumptions listed above, we found the surface and body wave amplitudes produced by the synthetic event were consistent with the recorded waves at MNTA and CUST. The other two stations (LBOH and SHNR) yielded broadly dispersed surface waves which had lower peak amplitudes in the frequency band from 2 to 10 seconds. This pronounced mismatch is not due to unmodeled source effects but results from the propagation of the energy through a crust that differs significantly from the 1-dimensional Prodehl model. Any com-

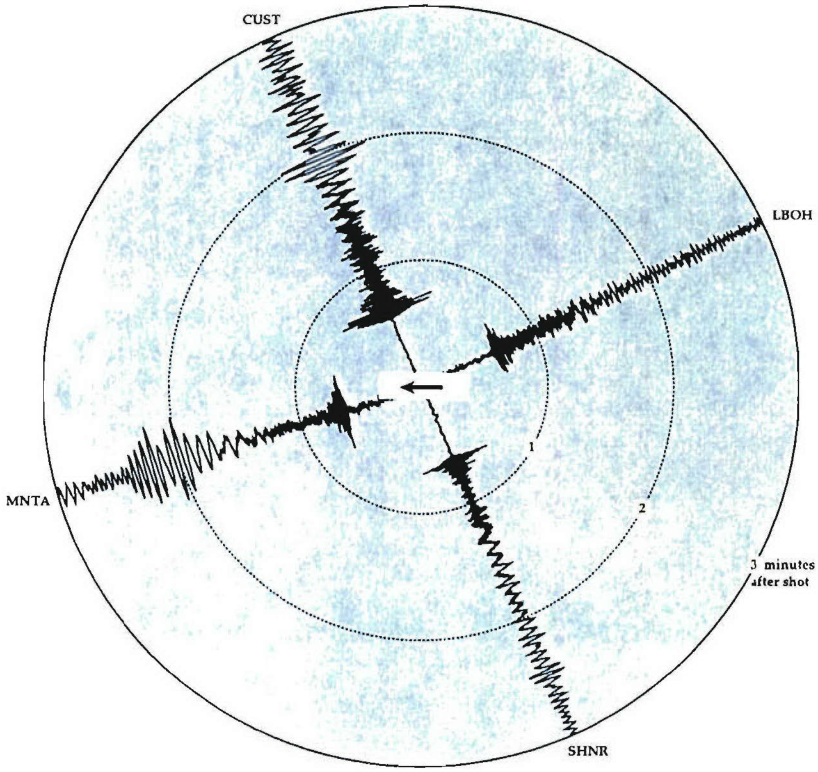


Figure 10. Unfiltered vertical component seismograms from the azimuthal network show the progression from high-frequency body waves to substantial surface waves. The July 19, 1996 blast used 4.5 million pounds of ANFO which detonated as planned. The arrow indicates the direction of shooting. The waveforms are highly dependent on azimuth. Propagation to the east across the Black Hills Pluton resulted in relatively little surface wave energy.

ments at this time on what these differences imply about the crustal velocity model would be imprecise. A surface wave inversion is currently being conducted by Rongmao Zhou and Brian Stump at Southern Methodist University. Although a significant azimuthal dependence of the surface wave amplitudes is observed, the surface waves produced by the cast blasts are significantly more energetic at all azimuths than those produced by the single shots. The relatively minor azimuthal dependence that is seen in the synthetics is due to source directivity.

2.6 Experiments in Varying Source Parameters.

Although we have reproduced the relative peak amplitudes of body and surface waves generated by the July 19 cast blast, several important questions remain unanswered. We have yet to determine which of the many source parameters included in the model play a leading role in generating the energetic surface waves. We need to gauge the sensitivity of the observed signals to changes in source parameters and to assess the utility of these signals for source characterization. Anandakrishnan et al. (1997) considered the effect of changes in several source parameters on regional waveforms. In this section, we conduct a similar exercise; however, we are most interested in how these changes affect the partitioning of energy between the surface and body waves. We focus on the frequency bands considered in Figure 9. We

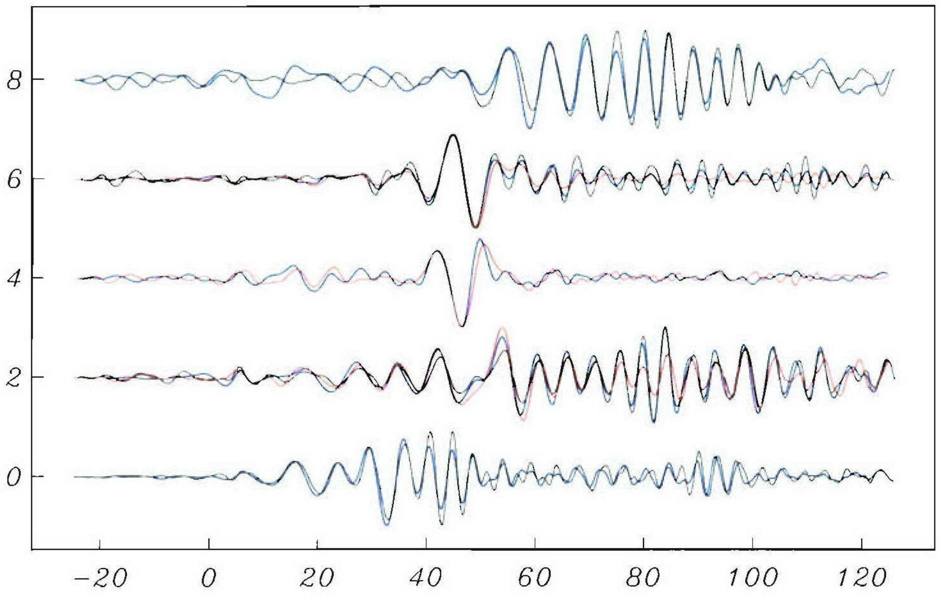


Figure 11. A comparison of band-pass filtered regional seismograms from three different cast blasts at five different stations at varying azimuths from the mine (see Figure 7). All of these blasts occurred in the south pit of the Black Thunder coal mine. All shots were detonated in the south pit of the Black Thunder coal mine (Figure 8). Low frequency seismic signals from the south pit events are robust although highly dependent on azimuth.

consider a broad suite of mine blasts. The blasts we synthesize are all the same as the presumed correct one reviewed in the previous section except one source parameter is allowed to vary while the others are held fixed. In turn, we vary the spalled mass, individual shot yield, and the duration of the blast. In a separate experiment we also allowed shot times to deviate from the planned 35 msec delays. All synthetics are calculated for CUST, the station located 200 km to the north of the mine. The results for the other three stations are essentially the same and are not plotted.

An example is shown in Figure 16 which displays synthetics for a suite of cast blasts in which the total yield of each shot hole is varied from 20% of the actual value to 200% (from 1468 to 14676 pounds). The synthetics suggest that the body wave amplitudes will scale rapidly with individual shot yield however the surface waves show a weaker dependence. This is consistent with ANANDAKRISHNAN ET AL. (1997) who concluded that the surface waves are mostly due to the different yield scaling in the explosion and spall source models.

A more general illustration of source effects on body and surface wave amplitudes is given in Figure 17. In the upper panel of this figure we consider peak amplitudes in two filtered versions of the synthetic traces. We filter the synthetic traces between 2 and 10 s, and between 1 and 10 Hz and calculate the log of the peak amplitude in each trace. In Figure 17, we display the ratio of the peak amplitude in the the low-frequency trace to that in the high-frequency trace. In the upper panel, we display the ratios obtained from synthetic events in which a significant source parameter has been varied between 2.5% and 500% of the standard value. As seen in Figure 16, the surface wave to body wave amplitude ratio decreases with increasing shot yield. This effect is represented by the filled circles in the upper panel of

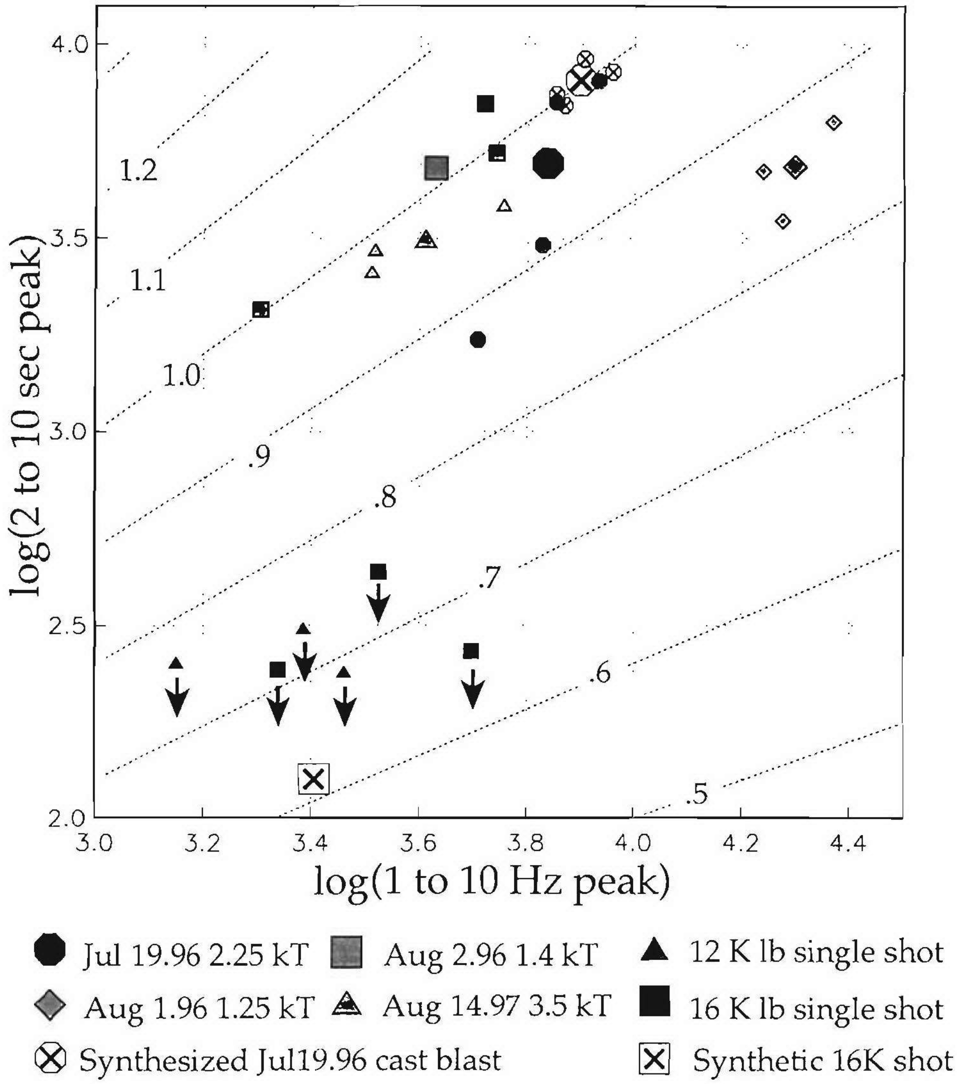


Figure 12. A comparison of 2 to 10 second surface wave and 1 to 10 Hz P wave peak amplitudes using recordings made at a range of 200 km by MNTA, CUST, LBOH & SHNR (Figure 7). All events occurred in the Black Thunder coal mine. Each trace is filtered, converted to an envelope and adjusted downward by an amount determined by pre-onset noise. Above are displayed the logarithms of the individual station peak amplitudes. The large symbols represent the network average for each event. Each labeled curve indicates a constant ratio of surface wave to *P* wave amplitude [*i.e.* log(2to10s peak)/log(1to10Hz peak)]. As expected the calibration shots yield essentially no surface wave energy above noise. The downward arrows indicate that the maximum *P* wave amplitude is well constrained but the surface wave amplitude lies below noise. For this reason, no network averages are displayed for these events. The Aug 1.96 cast shot appears as being somewhat explosion-like due to the sympathetic detonation. The sympathetic detonation greatly boosted P wave amplitudes but left the surface waves untouched. Unadjusted amplitudes are plotted as all stations are at the same range from the mine. We also display peak amplitudes from a synthetic version of the July 19 cast blast and from a synthetic 16,000 pound calibration shot. The energy partitioning from the synthetic events is in agreement with observations.

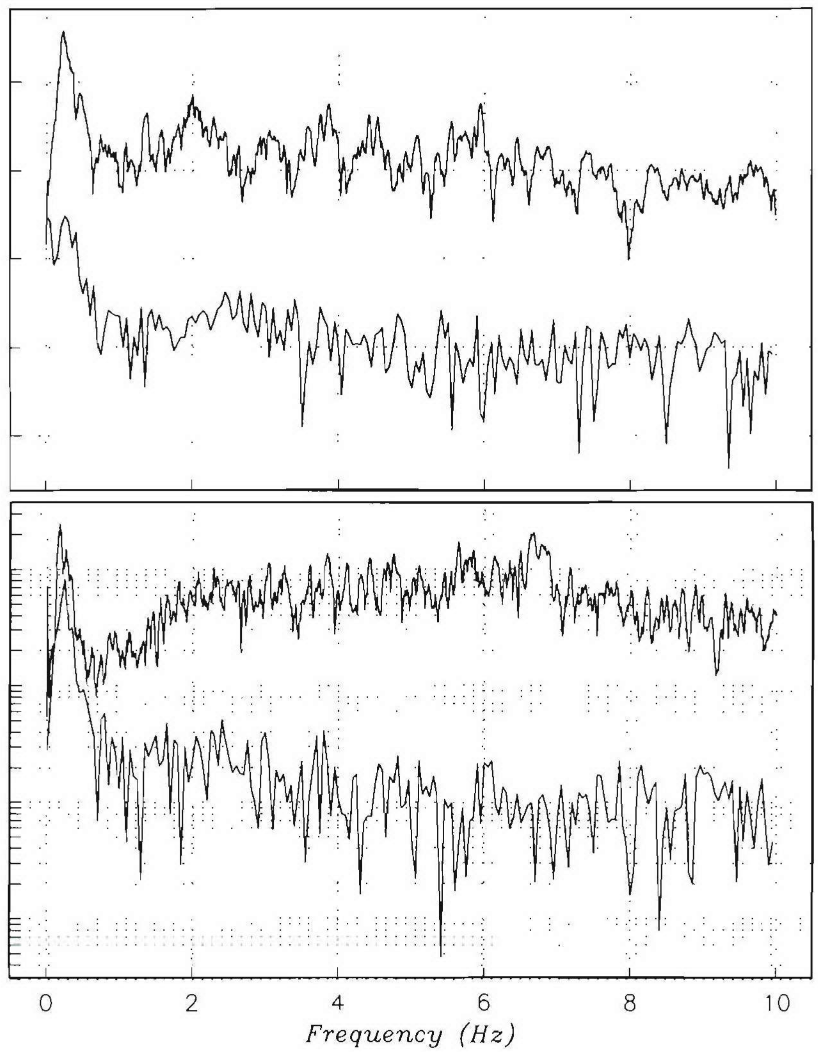


Figure 13. Spectral estimates taken from pre-event noise and signal recorded at CUST. In the upper panel, we display spectra taken from the recording of the July 19, 1996 cast blast (see Figure 6). In the lowe panel we display spectra taken from the CUST recording of the 16,000 pound calibration shot. The noise spectral estimates were untapered. Both P wave spectra have been convolved with a boxcar function spanning 0.04 Hz to give a clearer view of the spectral modulations in the upper panel.

Figure 17. This effect is seen to be relatively minor as varying the yield over more than 3 orders of magnitude (from 182 to 36,300 pounds) changes the body-surface ratio by ~ 10%. As seen in Figure 16, this ratio change results from changes in both the surface and body wave amplitudes.

Varying the spalled mass has the opposite effect. When the spalled mass is varied from 0.5 kt to 80 kt (from 2.5% to 400% of the standard) the surface-body wave ratio changes from ~ 0.9 to 1.13 (filled triangles in the upper panel of Figure 17). The change in this ratio results from the effect spalled mass has on the surface waves as the spalled mass is predominantly a source of low-frequency energy. Changing the spalled mass had little effect on the body wave amplitudes. Although the production of

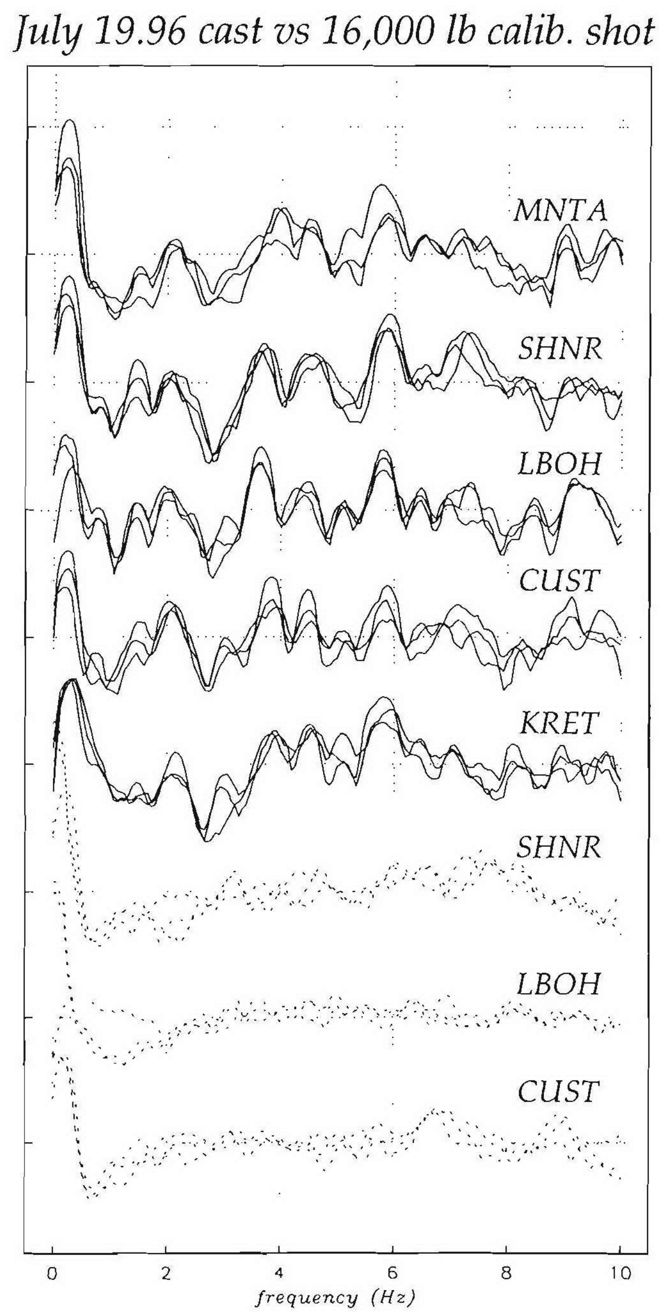


Figure 14. Obvious time-independent modulations exist below 10 Hz in the spectra of recordings of the Juy 19 cast blast (upper solid lines). At each station three curves, each representing the log of the spectral amplitude from a single component, are plotted. These are similar to the high frequency modulations observed by HEDLIN ET AL. (1989) although these are likely due to source finiteness and interrow delays. Both these spectra and those observed by HEDLIN ET AL. (1989) are independent of the recording direction. A very slight dependence of the modulations on azimuth can be seen. The 16,000 pound calibration shot (dashed lines) produced no discernable spectral modulations. Each detrended multitaper spectral estimate was taken from 125 seconds of P and S coda. All components, from each 3-component station, are plotted.

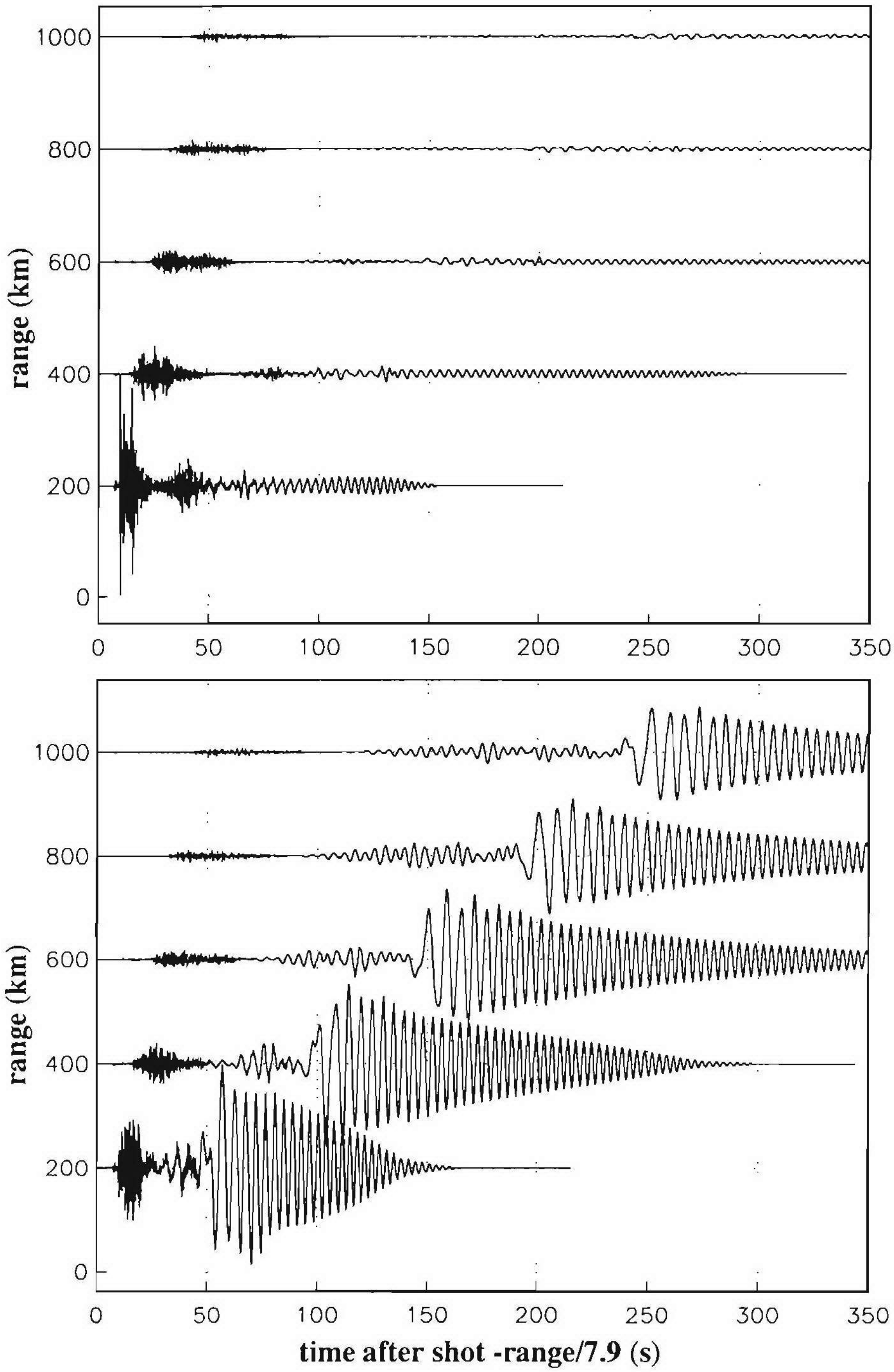


Figure 15. Simulations of two events. A single 16,000 lb shot is displayed on top, the July 19, 1996 cast shot is displayed on the bottom. The single shot is an insignificant source of surface waves. The surface waves excited by the cast blast decay relatively slowly and dominate the waveform of the cast shot at all ranges from 200 to 1000 km. The single shot synthetics are magnified for clarity. The range dependence of all synthetics was reduced by simply scaling all amplitudes by the range.

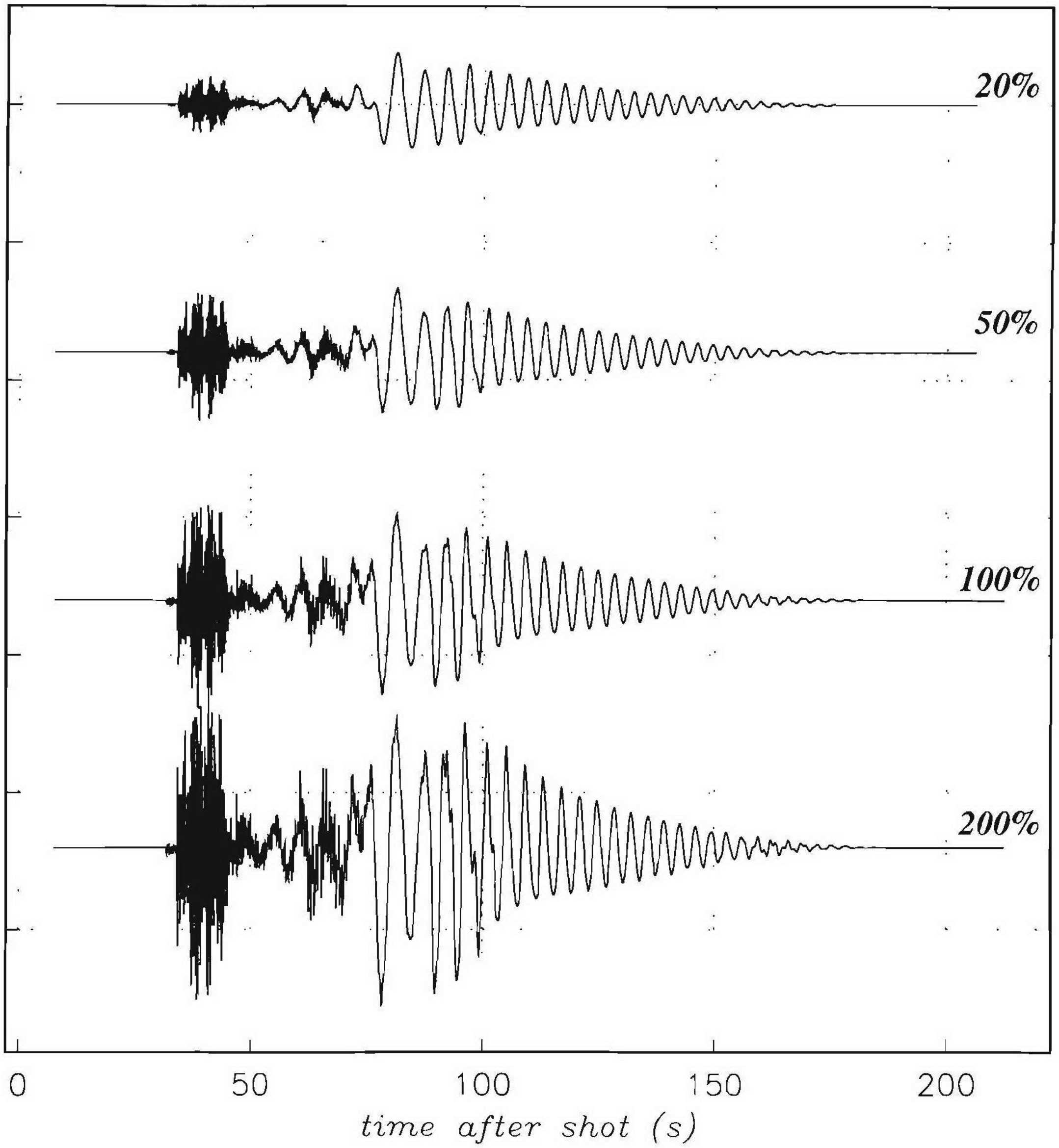
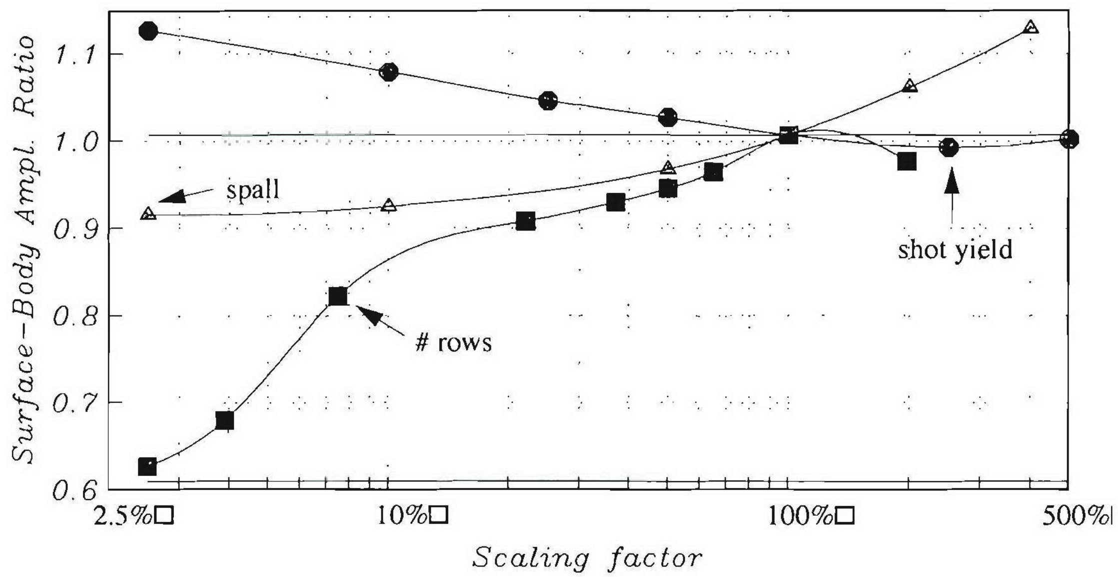


Figure 16. The dependence of vertical component waveforms on shot parameters is easily simulated using the MineSeis Matlab package. These plots show the dependence of the waveform on the yield of the individual shots. The standard cast, with individual shots of 7338 lb, is the third trace from the top. The scaling of the shot yield is indicated by the text to the right of each trace. The body wave amplitudes depend strongly on shot yield. The surface waves show a weaker dependence.

surface waves is reduced when essentially no material is spalled into the pit, the restricted blast still produces surface waves that are significantly more energetic than those produced by the single shot.

The most significant changes in the waveform result from variations in the total duration of the blast. To vary the blast duration we scaled both the number of rows and the number of shots in each row. The standard blast had 7 rows and 89 shots in each row and lasted a total of ~ 4.8 s. The largest blast grid we



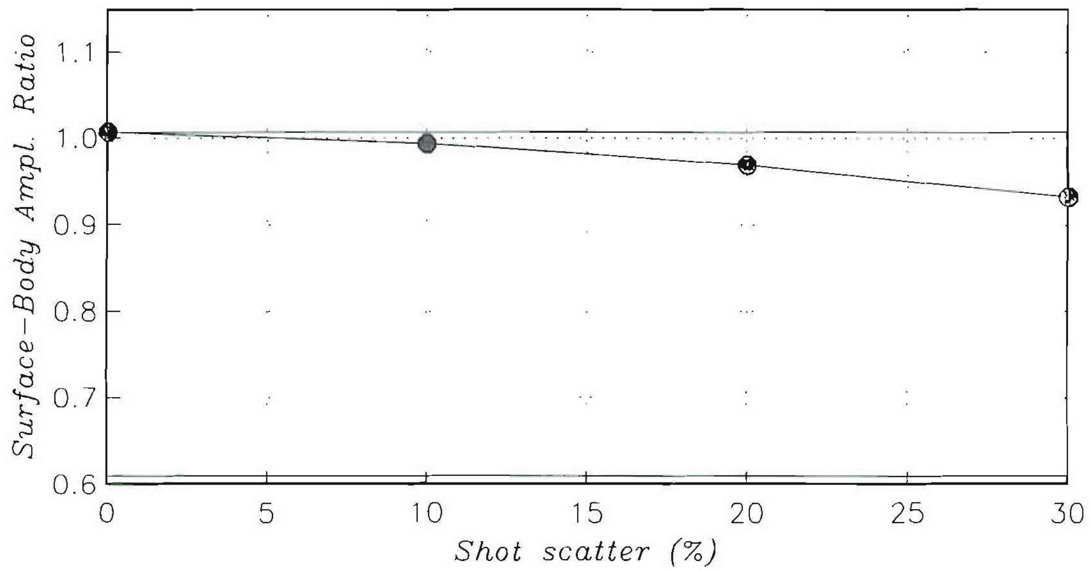


Figure 17. In the upper panel we display the surface-body wave ratios for a suite of blasts in which a single source parameter is varied while all others are held fixed at levels believed to be appropriate for the July 19, 1996 cast blast. The filled circles represent sources in which individual shot yield is varied from 182 to 36300 lb. The filled triangles represent blasts in which the spalled mass per shot is varied from .5 kt to 80 kt. The squares represent blasts grids that range from a single row with 3 shots to a 10 row blast with 200 shots in each row. Varying blast duration clearly has the most significant impact on energy partitioning. Only the severely restricted grid partitions energy like the synthetic 16,000 pound shot (represented by the horizontal line at a ratio of 0.61). All of these simulations assumed the subshots detonated exactly when planned. The curve in the lower panel represents blasts in which the shot times are distributed normally about the planned times. The shot scatter considered ranges up a variance of 30% of the planned intershot delay of 35 msec.

considered had 10 rows, each with 200 shots. The extended blast spanned ~ 9.5 s - ~ 200% of the actual duration and had a total yield of 14 million pounds. The reduced blast grids consisted of 5 rows, 50 shots per row; 4 rows, 40 shots per row; 3 rows with 30 shots per row; 2 rows with 20 shots per row and 1 row with 10 shots. To reduce the blast further we decreased the number of shots in the final row to 5 shots and then to 3. The duration of these reduced blasts ranged from 3.1 s (for the blast with 5 rows and 50 shots per row) to 70 msec (for the smallest blast). As we see in Figure 17, extending the blast beyond the standard one that was used on July 19 yielded essentially no change in the surface-body wave amplitude ratio. However reducing the scale of the grid has a significant effect on the partitioning of energy between surface and body waves. Reducing the scale of the blast has a modest effect on body-wave amplitudes but the surface waves are strongly dependent on this source attribute. The ratio drops most rapidly when the blast duration is reduced below 2/10 of the actual duration (down to ~ 0.5 s from 4.8 s). The production of 2-10 s surface waves is reduced significantly when the blast duration is reduced below 2 seconds. When the blast duration extends much beyond 5 seconds, production of these surface waves is not increased substantially. Of all the blasts considered, just the brief blast resembled the single shot (which is represented by the horizontal line at a ratio of 0.61).

All synthetics considered thus far assumed a perfect temporal and spatial adherence of the actual shot grid to the design grid. Introducing shot time scatter, which is believed to be omnipresent (STUMP AND REAMER, 1988; STUMP ET AL., 1994,96), is predicted to have no effect on the surface wave amplitudes but could increase the body wave peak amplitudes significantly (Figure 17; lower panel). Shot scatter increases the likelihood that shots will detonate simultaneously. An extreme example of shot scatter is the simultaneous detonation of a portion of the shot grid. This occurred in the August 1, 1996 blast and, as predicted by the synthetics, the surface waves were not affected (Figure 12). The network averaged peak surface wave amplitudes for the three mine blasts shown in this figure are very similar, despite the wide range of explosive yields. It appears that surface waves are just generated by temporally extensive mine blasts without regard for exactly how the blasts are detonated, and whether the blast sequence includes any significant detonation anomalies. The anomalous event was assigned a body wave magnitude of 4.0 (REB bulletin).

2.7 Synthesis and Automated Recognition of Spectral Modulations

*2.7.1 Synthesis.*Seismic signals produced by delay-fired sources have spectral modulations at a wide range of frequencies. High-frequency modulations result directly from intershot delays. These delays are typically 35 msec and the modulations occur at multiples of 1/35 msec (~ 30 Hz). Interrow delays are typically longer. The cast blasts we consider in this section have interrow delays of 200 to 300 msec which give modulations every ~3 to 5 Hz. Source finiteness will also cause subtle modulations spaced at the inverse of the duration of the event (*e.g.* GITTERMAN AND VAN ECK, 1993). Spectral modulations can also be acquired during propagation to the receiver (HEDLIN ET AL., 1989). To illustrate this problem, and to illustrate the modulations that can result from source finiteness, we consider two synthetic sources - a single shot and a simple, 1 row, 25 shot delay-fired source. As shown in Figure 18, a single shot yields spectra with subtle modulations. These modulations are due to resonance in the near-surface layer of the model. This layer has a two-way travel time of ~0.4 s and thus produces modulations spaced at ~2.5 Hz. Much more significant modulations below 10 Hz are produced by the delay-fired event. The simple delay-fired event consisted of a single row of 25 shots. Intershot spacing of 35 msec produces a high-frequency modulation starting at 29 Hz (1/0.035 s). The shot sequence lasts for 0.875 s. The source finiteness causes a spectral modulation at the inverse of the source duration (peaks every 1.14 Hz).

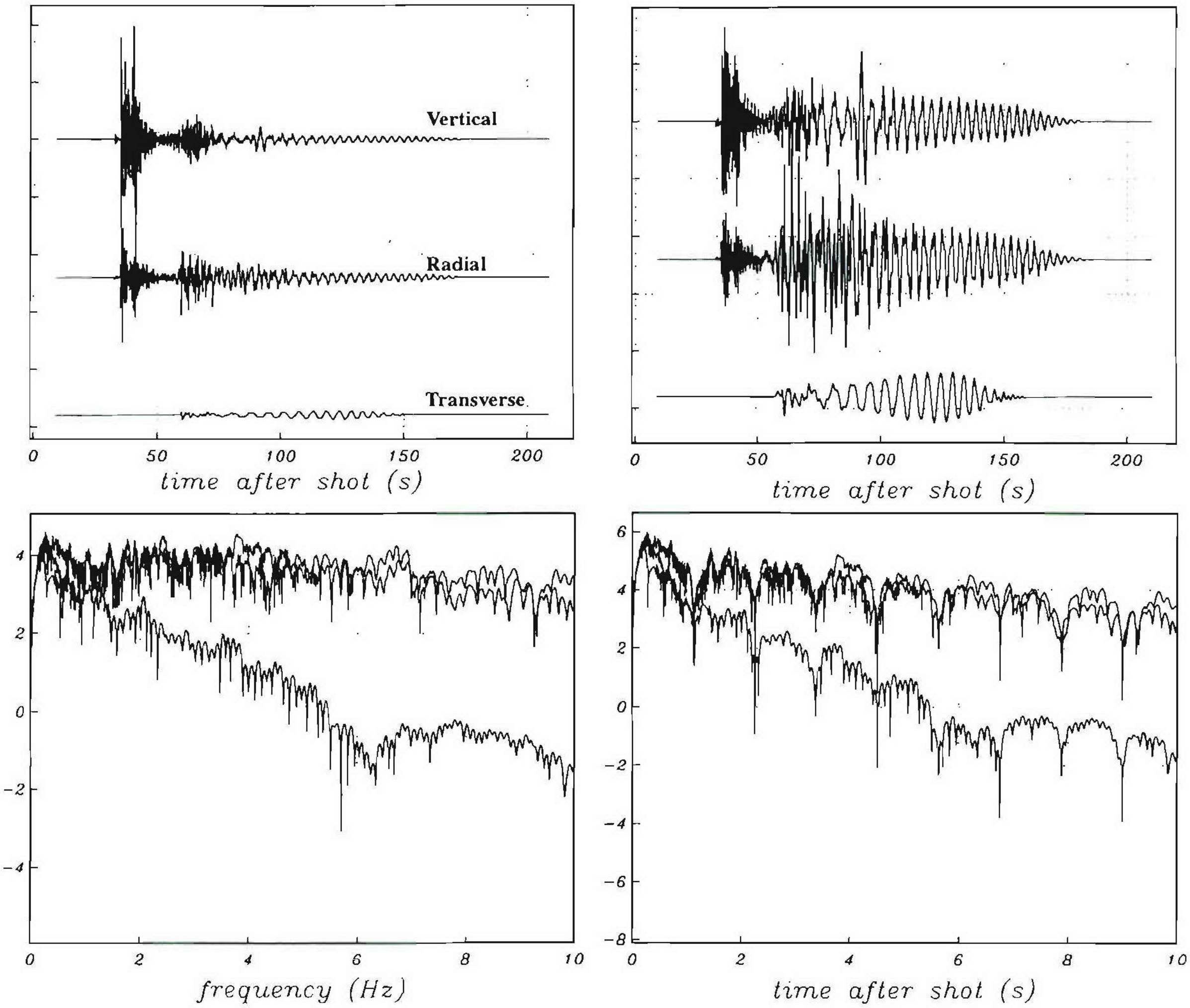


Figure 18. A synthetic 16,000 lb single shot at a range of 200 km is shown on the left. The faint spectral modulations seen in the spectra are due to resonance in near-surface low-velocity strata. A simple cast blast consisting of 1 row of 25 shots spaced at 35 msec is shown on the right. This simulation is for a station at a range of 200 km. The prominant modulations seen in the untapered spectral estimates are due to source finiteness. This shot lasted .875 s and produced modulations at the inverse of the duration (1.14 Hz). The first peak due directly to the intershot delays lies at 29 Hz.

To understand better the modulations produced by the July 19 event, we contrast signals from 3 different blasts with those produced by an instantaneous shot. Starting at the top of Figure 19, the upper three black traces are modulations between 1 and 10 Hz predicted for 1, 4 and 7 row cast blasts respectively. These synthetic blasts are modeled after the July 19 decked blast, we have just altered the number of rows. The dashed spectra were taken from a synthetic 16,000 pound instantaneous shot which was located at the same point. In the single row delay fired event we see broad modulations spaced at ~ 2.5 Hz and fine-scale modulations spaced at ~ 0.3 Hz. The fine scale modulations are due to the finiteness of the source (which spanned ~ 3 s). The broader modulations are seen in the spectra from both sources and are due to resonance. Strong modulations spaced at ~ 0.75 Hz appear in the spectrum of the 7 row blast. These are not continuous across the band from 0 to 10 Hz but appear to be strongest at ~ 3 Hz.

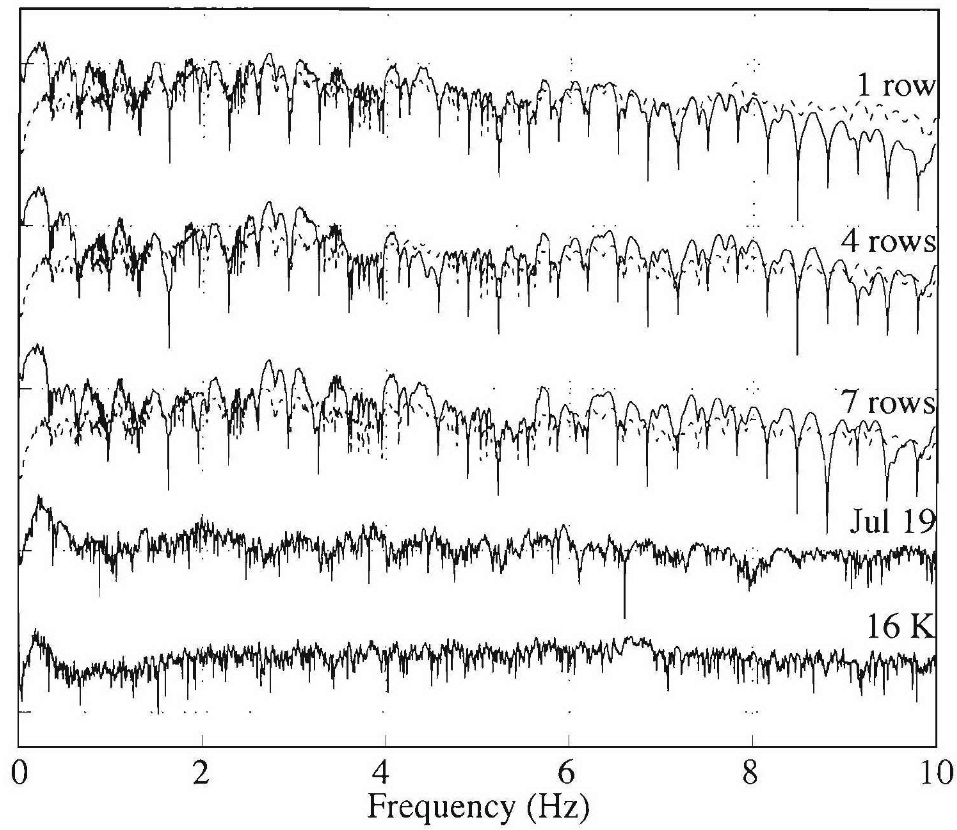


Figure 19. A comparison of spectra from synthetic and real events. The upper three black traces are vertical component spectra from synthetic cast blasts that are based on the July, 1996 south pit blast. The third spectrum is calculated from the full 7 row shot pattern. The middle and upper traces were calculated by using the front 4 and 1 rows respectively. The grey curve plotted with each spectrum is from a synthetic 16,000 pound calibration shot. All synthetics were calculated for a receiver located 200 km to the north of the mine at the CUST station. The fourth spectrum is from the CUST vertical component of the July 19 event. The lowest trace is from the recorded 16,000 pound calibration shot. Broad modulations seen in all synthetic spectra result from resonance in the 1-dimensional model. The fine-scale modulations are a source effect. Although the synthetics do not reproduce the fine detail of the low-frequency spectra recorded by the regional network, they do reproduce the general periodicity and variance of the modulations. In this figure, all spectral estimates are untapered.

These modulations are not present in the spectra of the single-row blast and are due to the combined effect of the interrow and interdeck delays (which range from 0 to 300 msec) and source finiteness. Although the 7 row event had a total duration of ~ 5 s, the rate at which explosives were detonated was strongly dependent on time. The first shot in the final row detonated ~ 1.9 s after the shot sequence began. The final shot in the first row detonated ~ 3.2 s into the sequence. For 1.3 s in the middle of the shot grid, all 7 rows were being detonated and the explosive yield per time delay was at a peak (~ 25,000 pounds per 8 msec delay period). The spectral modulations produced by this trapezoidal source time function are not spaced at the inverse of the total shot duration (~ every 0.2 Hz) but rather are more broadly spaced at ~ 0.75 Hz (the inverse of the 1.3 s period during which explosive yield is at a peak).

These fine scale modulations are not continuous across the band from 0 to 10 Hz because of destructive interference with long interrow and interdeck delays.

The fourth spectrum displayed in Figure 19 was taken from the vertical component recording of the July 19 event made at CUST. At the bottom of this figure we display a spectrum taken from the CUST recording of the 16,000 pound calibration shot. Strong peaks are observed in the cast blast spectrum at 2, 4, 6 and 10 Hz (see also Figure 14). Smaller modulations are seen across the band from 1 to 10 Hz at a spacing of ~ 0.75 Hz. These modulations are not seen in the spectrum of the calibration shot and are clearly a source effect. These modulations require source delays of > 1 s to 500 msec. The synthetic test displayed in the upper part of this figure suggests that these modulations are due to the combined effects of source finiteness and the complex interference between the 7 rows and 2 decks at this source; however, the fine spectral details are not reproduced.

We lack the necessary ground truth information to reach definitive conclusions regarding probable causes of the mismatch between the observed and synthesized modulations; however, unmodeled source effects such as shot time and yield scatter seem most likely. The synthetic events we considered in this experiment consisted of shots that had exactly the same yield and detonated exactly when they were supposed to. Any deviations from uniform spacing of identical shots will change the manner in which signals from the different source processes (finiteness, interrow, interdeck and intershot delays) interfere with one another and will cause the recorded modulations to differ substantially from those predicted by synthetics. The synthetics suggest that most modulations observed in the recorded cast blast are due to long source delays and to source finiteness; however, this observation remains tentative as the fine details of the spectral modulations are not matched.

*2.7.2 Automated Recognition.*HEDLIN (1997; 1998a,b) used a variant of cepstral analysis to quantify time-independent spectral modulations at high frequencies (up to 40 Hz). The standard cepstrum is the Fourier transform of the log of a single spectrum. Hedlin used the 2-dimensional Fourier transform of sonograms to isolate spectral energy that is periodic in frequency and independent of time. The same processing technique can be used for the low-frequency modulations observed here. Figure 20 shows discrimination parameters output by the Automated Time Frequency Discriminant (ATFD) for individual stations. The 3 parameters displayed are the autocorrelation, which measures the independence of spectral modulations with time; the cross-correlation, which measures the independence from recording component; and cepstral extreme, which indicates the strength of time-independent spectral modulations. Although there were too few ground-truthed events to put the output to a statistical test, we tentatively conclude that the network averaged parameters separate single explosions from cast explosions.

2.8 IMS Recordings of the July 19, 1996 cast blast

The regional experiment provided evidence that large mining events will routinely yield significant low-frequency seismic signals. This network was deployed within 2° of the Powder River Basin so this test is rather unrealistic. Under a foreseeable monitoring scenario, where the bulk of the data comes from IMS stations, these events will be detected from mid-regional range. Detection statistics from the PIDC show that many of the PRB explosions are seen at far-regional to teleseismic range but can these attenuated signals be used for source characterization?

IMS recordings of the Wyoming events can give some indication of the range from which these signals might be used for source characterization. As shown in Figure 21, a low-frequency surface wave packet from the July 19, 1996 Black Thunder blast are seen out to ULM at a range of 9.1°. Figure 22 shows

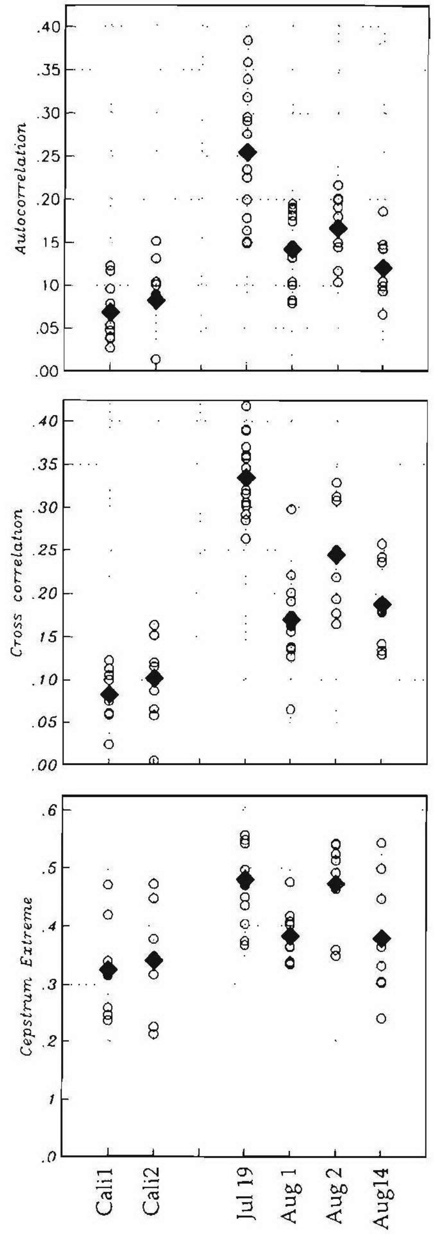


Figure 20. Discrimination parameters calculated by the Automated Time-Frequency Discriminant (ATFT, are described in detail in HEDLIN, 1998. Each panel shows the results of applying a single operator to the time-frequency expansions of the data. The autocorrelation operator (top panel) assesses the dependance of the spectral modulation pattern on time. The cross-correlation (middle panel) is a measure of the independence of the modulation pattern from the recording component. The cepstral extreme (bottom panel) is a measure of the amount of energy in the coda that is periodic in frequency and independant of time. Each 3-component recording gives rise to 9 parameters - 3 from each operator. Two calibration shots (left) and four cast blasts (right) were considered. The large symbols represent unweighted network averages.

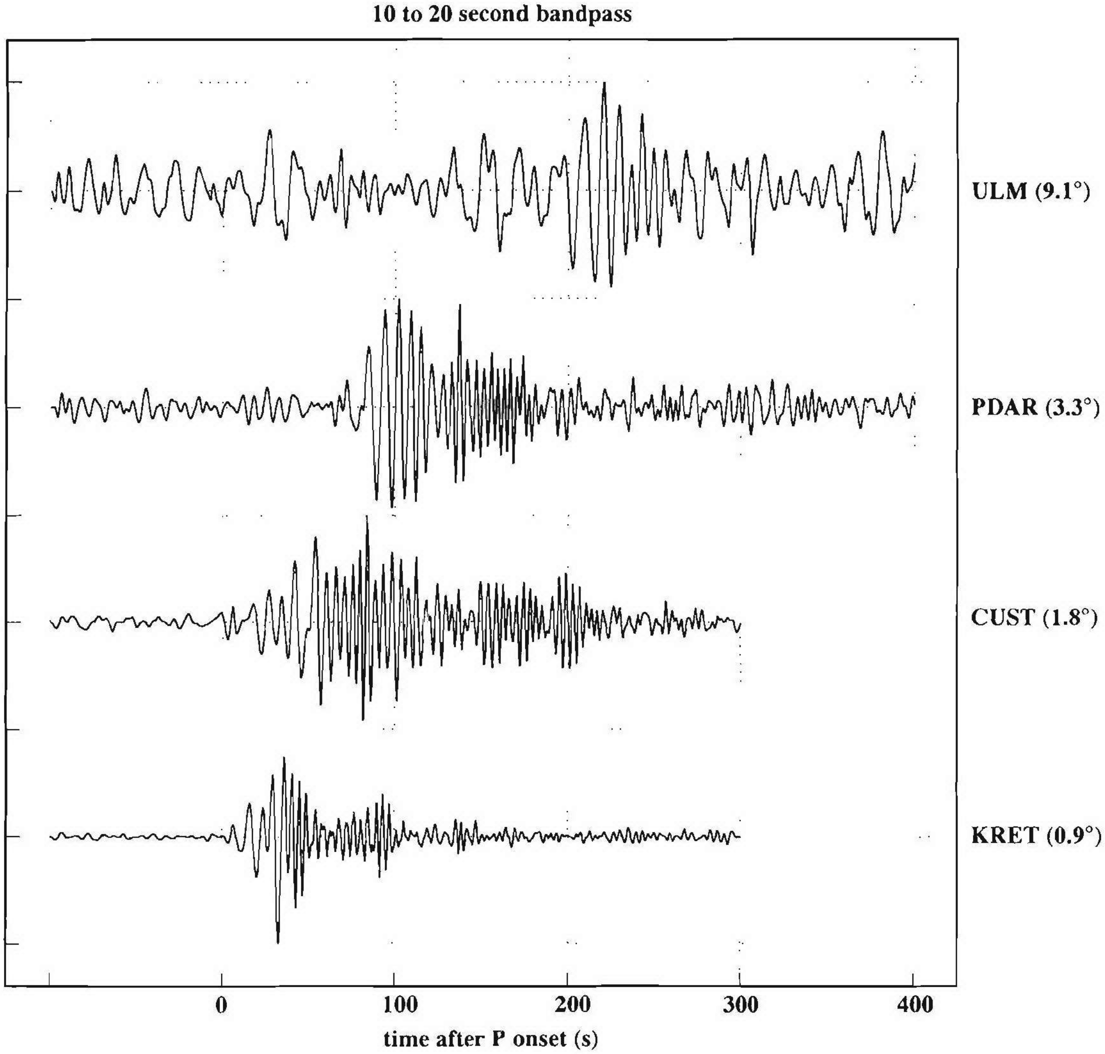


Figure 21. IMS/WYnet recordings of the Jul19, 1996 cast blast. The low-frequency bandpassed recordings exhibit an energetic dispersed surface wavetrain out to the IMS station ULM at 9.1°.

that the low-frequency spectral modulations also survive to this range; however, those above 6 Hz have fallen below noise.

2.9 Discussion and Conclusions

2.9.1 Mining explosions and the CTBT. Under a CTBT, mining explosions will be problematic. As these events occur worldwide, many produce significant seismic signals which can be detected at mid- to far-regional and to teleseismic distances. Mining blasts are exceedingly complicated events. The complexity in the cast blasts considered in this section stems primarily from the interaction of delay fired explosives, rock fracture, and spall. The challenge mining events pose for the monitoring community is heightened because, through time, mine operators will occasionally experiment with new shot patterns. Furthermore, mine blasts will typically not detonate exactly as planned. Most deviations

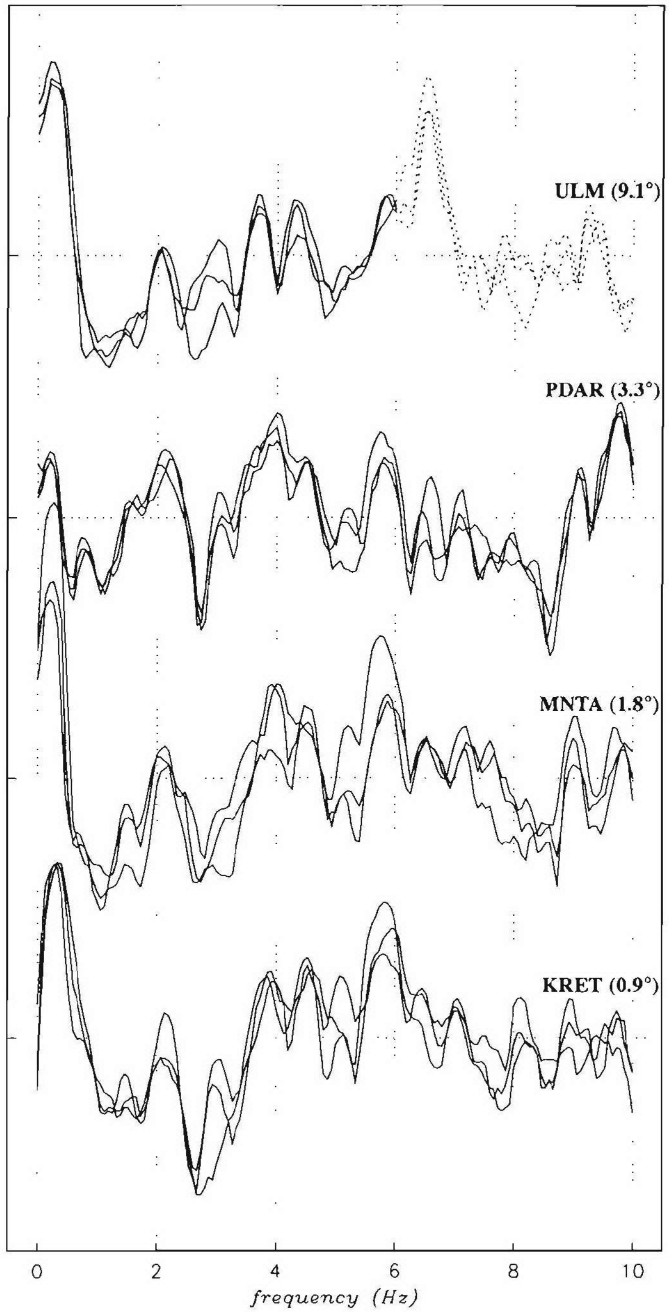


Figure 22. Multitaper spectral estimates taken from IMS and WYnet recordings the July 19 cast blast. The dashed portion of the ULM spectrum is noise. This robust low-frequency spectral roughness is not produced by small single explosions (Figure 10).

from the planned shot grid, such as shot scatter (e.g. Stump and Reamer, 1988), are not highly significant. Other anomalies, such as the sympathetic detonations discussed in the introduction, are relatively infrequent but can be significant. A constraint is also placed on characterization methods by the IMS stations which sample the signal at 40 sps. Most diagnostic signals due to intershot delays are beyond the recording Nyquist frequency and are likely to be attenuated. For these reasons, we believe that it is important that a suite of approaches are developed to characterize these events. Under the

CTBT, monitoring of mining blasts at any range will have to rely heavily on low-frequency signals.

2.9.2 The relative merits of the discriminants. Methods based on spectral modulations are potentially useful. For this approach to have value, it is necessary to separate modulations acquired at the source from those acquired during propagation and from those present in the background noise. Techniques that are dependent on high frequency modulations are typically limited to near-regional ranges and settings where the propagation Q is high (e.g. stable cratons). For this reason, this section has focused on the causes of modulations below 10 Hz. It is apparent that complex mining blasts produce spectral modulations at a broad range of frequencies. The Wyoming field experiments have provided evidence that significant mining explosions will produce spectral modulations below 10 Hz that are not single-explosion like. Low frequency modulations below 5 Hz will be detected beyond near-regional range. Just how common these signals are beyond near-regional range, and whether they are noticeable at lower blast yields is implied by our analysis of synthetics and by the recordings at ULM but will require further study of recorded events. The path from Wyoming to ULM probably has a relatively high propagation Q. As a result, this observation cannot be taken as representative most regions but is the kind of scenario one might expect in a stable continental region. One region in which large mining blasts are not uncommon and propagation Q is relatively high is the Kuzbass/Abakan mining region in Kazakhstan. In regions where propagation Q is low, such as Wyoming, the high frequency modulations due to intershot delays are quickly lost, although those due to longer duration source processes remain.

Long period surface waves from large mining blasts in Wyoming are readily seen at mid-regional distances. The expenditure of a lot of energy spread out in time results in body waves that are relatively inenergetic and surface waves that are large. Our experiment indicates that the energy partitioning of mining blasts is not explosion-like and might be useful at mid-regional distances. It is clear that in geologically complex regions like Wyoming, surface waves are highly dependent on the path (Figures 7 to 12). Even in this region, however, our study indicates that peak amplitudes along paths where surface waves are rapidly dispersed are high.

Our analysis of a small number of events indicates that the observables (spectral roughness, energy partitioning) can be reduced to simple discrimination parameters. This result indicates that the ATFD approach developed by Hedlin (1997, 1998a,b) can be simply scaled to lower frequencies where necessary. We have not yet attempted to define similar discrimination parameters for the body-surface amplitude ratios. In large part, this is due to a shortage of events included in the analysis and a shortage of recordings at ranges other than 200 km. A number of researchers (incl. Anandakrishnan et al., 1997 and Stump and Pearson, 1997) have pointed out anomalous surface waves . If this observation appears to be routine from studies of events from other regions the next logical step is to take source-receiver range into account and define a Mb:ms relationship for mining blasts.

The potential for misidentifying a mining blast by using any one of these individual tools is rather high. It will, no doubt, be necessary to regionalize these techniques by examining, in detail, blasting practices and propagation in each area of interest. These tools will, perhaps, some day be used alongside other tools, such as cross-correlation, that have been proven to be powerful by a number of researchers.

2.9.3 Simulations. The state of the art in simulating mine blasts is not able to match wiggle for wiggle the seismic waves from these very complex events in the time or in the frequency domain. However, general features of these events (energy partitioning between body and surface waves, enhanced spectral roughness below 10 Hz) have been reproduced. We have used the synthetics as an interpretation tool to reproduce the general character of these events to better understand which source processes are

important, but an exact replication might never be realized.

There are several likely causes of the misfit. The code makes a number of assumptions about these sources that limit how well we can fit the data. Non-linear interactions between shots are not taken into account and are likely important (Minster and Day, 1986). The model assumes 100% of the spall kinetic energy converts into seismic. It is known that much of this energy is used to compact the spalled mass by collapsing voids and fracturing the rock, more energy is irretrievably lost to friction; however, these losses are not well understood at this time and are not taken into account in this code. As a remedy, this loss of energy can be modeled to some degree by assigning a smaller amount of spalled mass. The spalled mass is directly proportional to the seismic energy the spall generates. All shots in the blast are assumed to be identical. However it is well known that explosive yield is highly variable. Stump et al. (1999b),c analyzed single-fired shots ranging in explosive weight from 5500 to 50000 pounds. They found amplitudes from several 5000 pound shots varied by up to 2 orders of magnitude. The calibration shots considered by Stump et al. (1999b) were,c ~ 30 m apart at the same vertical depth and so it is unlikely that changes in the physical properties of the medium are the cause of this variable performance. Velocity of detonation measurements in the holes were not made although video footage indicates a lot less borehole response in terms of motion and permanent displacement around the borehole for the event producing the smaller motions. These arguments support degraded explosive performance.

Other processes associated with each shot (e.g. spall tonnage and throw direction) are also assumed to be identical. Decorrelation between shots is also unavoidable (Stump et al., 1999b) and will ,cdegrade the constructive interference (Baumgardt, 1995). The analysis of single shots conducted by Stump et al. (1999b),c indicates that for the shot separations commonly used in these mining blasts (~ 10 m) we should expect good correlation below ~4-5 Hz. Decorrelation is not taken into account in the current code as all sources are assigned a common Green's function. Shot timing is also an issue. We have concluded that low-frequency modulations result from long source delays and source finiteness; however, the fine details of these modulations are dependent on the interplay, or interference, between these processes. Marked changes in the modulation patterns can be caused by making seemingly minor adjustments in the shot pattern. Shot scatter, or the mismatch between intended and actual shot detonation times, is ever present (Stump and Reamer, 1988) and is not taken into account in our simulations.

Despite these limitations, synthetics reproduce the general character of the spectral modulations observed and indicate that, in the absence of strong crustal resonance which will also yield spectral modulations, this trait can be useful for separating delay-fired blasts from instantaneous explosions. The synthetics underscore the need for taking into account seismic resonance. In the 1-dimensional model, the low velocity surface layer is continuous between the source and receiver. In practice, seismic resonance will be observed if the layer is discontinuous and present only at the source or at the receiver.

The energy partitioning between body and surface waves is more easily reproduced. The synthetic test clearly indicates that source duration has the most significant effect on surface wave amplitudes. Spall is a second-order effect. This successful simulation gives a physical basis to the surface waves observed. The source parameter tests are a first step in using synthetics to gauge the sensitivity of surface waves to changes at the source.

2.9.4 Outstanding Issues. This empirically based study has identified a number of characteristics of seismic waves from large scale cast blasting that can be used for identifying the source. Within the context of the CTBT, the extent to which this observational experience can be used to assess discrimination techniques in other regions where propagation path effects are different and blasting practices may vary needs to be assessed. In some of these other areas there may be little or no access to

information concerning blasting practices and so it is hoped that these detailed studies may provide the foundation for the interpretation of the observations after consideration of propagation path effects.

A number of outstanding issues associated with the generation of regional waveforms from mining explosions remain independent of specific information on propagation paths. Mechanisms for the generation of regional surface waves have been demonstrated but need further investigation and constraint. The impact of a range of blasting practices from long time duration cast blasting in coal mines to short duration rock fragmentation blasts in surface coal mines needs to be explored. The modeling and data analysis has assumed that design blast parameters are those that are implemented. For purposes of assessing the reliability of discriminants, the quantification of anomalies in blasting and their implications for regional seismograms needs additional exploration. Finally this study has focused on observations from mining and single-fired explosions but has not compared these observations to those from earthquakes along similar propagation paths. Studies which include earthquake and mining explosion sources along comparable propagation paths will allow the assessment of the proposed discriminats for separating earthquake and mining explosion populations.

This study has focused on seismic observations from mining explosions. There is increasing evidence that infrasonic observations may help in the identification of surface mining explosions (SORRELLS ET AL., 1997). It is possible that the co-location of seismic and infrasonic instrumentation surrounding mining regions may significantly add to the identification capability of mining explosions.

Mining events are controlled and thus might provide an opportunity for clandestine tests as part of an advanced nuclear weapons program. There is a strong incentive for learning how to use the IMS to distinguish anomalies from clandestine nuclear tests and avoid On Site Inspections.

Unannounced mining events that include significant simultaneous explosive energy releases are problematic for several reasons. Such blasts are unwanted by the mining community as these events have both reduced rock-fracturing efficiency and increased seismic efficiency. Some of these blasts will trigger the IMS and cause some to question whether the anomalous energy release was chemical in nature. Effective characterization techniques, which rely on remote IMS observations, will reduce the need for on-site inspections. Our preliminary analysis suggests that such events can be identified using spectral modulations and the relative strength of surface and body wave seismic energy. A fuller analysis of errant blasts will be the subject of a forthcoming paper.

Section 3
Characterization of Mining Explosions at Regional Distances

3.1 Summary

This section presents a summary of a review paper entitled "Characterization of Mining Explosions at Regional Distances" written by Brian Stump, the PI, Craig Pearson and Vindell Hsu and published in the Reviews of Geophysics *(40(4), 1011, doi:10.1029/1998RG000048, 2002).*

The International Monitoring System that is being constructed in support of Comprehensive Nuclear-Test-Ban Treaty introduces new opportunities to nuclear test monitoring provided by wide access to data from seismic, hydroacoustic, infrasonic and radionuclide sensors. These sensors will detect a myriad of natural and man-made events and can be used to identify events that have explosive characteristics and might be clandestine nuclear tests. Detection and identification of seismic events will be at a lower magnitude threshold ($m_b = 3.5$ and lower) than has been previously considered. Concomitant with the lower monitoring threshold will be an increased number of events that must be scrutinized. This collection will be largely composed of regional observations in which the seismic waves have traversed complex geological structures. Improved regional geophysical models will be needed to support accurate location and source identification. Source identification will not be limited to the separation of single-fired nuclear explosions from earthquakes as in previous testing treaties. The lower magnitude threshold and increased reliance on regional observations suggests that mining explosions will be detected by the monitoring system. It is important that the signals from mining explosions are properly identified to avoid possible false alarms of the monitoring system. Cooperation with the mining industry, including deployment of close-in instrumentation and extensive documentation of the explosions, provides critical information for interpreting the performance of discriminants. Linkage of these observations to appropriate physical models of the blasting process is also enhanced through this cooperative research effort. A number of discriminants for characterizing mining explosions have been identified, including surface wave to high frequency body wave amplitudes and low frequency spectral modulations. Variable performance of individual discriminants results from such factors as mine specific blasting practices and the complexity of the regional wave propagation. This variability attests to the need for a suite of discriminants. Broadband data provides the basis for the most robust set of discriminants. The inclusion of infrasonic data as part of the IMS introduces a potential for the combined use of seismic and infrasonic data for the identification of near-surface explosions. The generation and, to a lessor extent, the propagation of mining explosion infrasonic signals is not well understood but empirical data attests to its future utility. Observational evidence for the accidental, near-simultaneous detonation of a large amount of explosives during standard delay-fired explosions is presented. These events have single-fired characteristics and may prove to be problematic in discrimination analysis.

3.2 Monitoring objectives

Increased interest in monitoring lower magnitude events (Mb 3.5 and lower) increases our reliance on regional observations. There remain unanswered questions associated with the detection, location and identification of small events using regional seismic data. The National Research Council in its report, Research Required to Support Comprehensive Test Ban Treaty Monitoring (National Academy Press, 1997) has stated that research in a number of seismological areas is needed to reach acceptable monitoring goals. Seismic research recommendations proposed by the NRC include: (1) Improve characterization and modeling of regional seismic wave propagation effects; (2) Improve capabilities to detect, locate, and identify small events using sparsely distributed seismic arrays; (3) Perform theoretical and observational investigations of the full range of seismic sources; and (4) Develop high-resolution veloc-

ity models for regions of monitoring concern. Complementary recommendations were made for problems associated with infrasonic, hydracoustic and radionuclide monitoring as well.

Event characterization procedures must identify a nuclear explosion, even if the explosion is conducted in an environment designed to hide or mask the identity of the signal. This challenge is balanced in a practical way by a need to minimize false alarms - naturally occurring or man-made events that exhibit some characteristics of a nuclear explosion. The successful monitoring system must be robust in identifying nuclear explosions while producing few false alarms by correctly identifying non-nuclear explosions such as mining blasts. This section will explore the characteristics of seismic and infrasonic waves from mining explosions that may provide for the most robust identification of these events.

3.3 Event characterization techniques

While significant mining activity occurs worldwide, blasting practices are tailored to local needs and are thus highly variable. Development of a strong physical basis for identification of mining blasts provides the foundation for implementation of characterization tools that can take this variability into account. It is important to link regional signal characteristics directly to documented blasting practices and phenomena.

Since the early 60's (Devine, 1962; Devine and Duvall, 1963; Pollack, 1963; Frantti, 1963), research has been conducted to develop techniques for identifying mining explosions. We now review these tools illustrating some of them with data and document the source processes that are responsible for the identification. No single tool will identify all mining explosions nor distinguish a nuclear explosion from all mining explosions. Successful event identification with a minimum of false alarms must employ as many of these tools as possible, thus protecting against isolated failures of individual tools. Special consideration is given to techniques that separate single-fired, contained explosions from delay-fired explosions typical of mining operations (Baumgardt and Ziegler, 1988; Smith, 1989; Hedlin *et al.*,1989; Chapman *et al., 1992).* Those characteristics that are similar for mining explosions and single-fired, contained explosions can also be used.

Some event characterization techniques are illustrated with observational data from a set of regional experiments based upon large-scale coal cast blasting and contained single-fired calibration explosions conducted in the Powder River Basin of NE Wyoming (Pearson *et al.*, 1995; Hedlin *et al.*, 2002). These blasts are used because they were well documented with cooperation of the mine. This ground truth information is critical to the physical understanding of the resulting discriminants. Regional observations were obtained from portable broadband stations at 100 to 200 km and the IMS primary array, PDAR, at 360 km from the mine.

We now turn to the central focus of this section that is a discussion of the collection of tools used for identifying mining explosions.

3.3.1 Surface Wave to Body Wave Amplitudes Recent work (Barker *et al.*, 1993; Bonner *et al.*, 1996; Anandakrishnan *et al.*, 1997) has investigated long period surface wave and short period body wave excitation at regional distances for both typical mining explosions and single-fired contained explosions. These studies suggest that the large cast blasts associated with overburden removal in surface coal mines exhibit enhanced long period motion when compared to single-fired contained explosions. The utilization of broadband data may provide a mechanism for separating some types of mining explosions from single-fired contained explosions. The long duration of many cast blasts (several seconds) and the mass of the material that is cast into the open pit of the mine may account for this earthquake-like characteris-

tic (enriched surface wave energy). The separation of the explosion population (single and cast) from earthquakes will not be addressed in depth.

3.3.2 P/L_g at high and low frequency One of the most robust regional discriminants for separating earthquakes from explosions has been the high frequency ratio of P to L_g energy in comparison to low frequency ratios for the same phases (Dysart and Pulli, 1990; Baumgardt and Young, 1990). Explosions and earthquakes show a small P to L_g ratio at intermediate frequencies (~1 Hz), while explosions show a large ratio at the higher frequencies separating them from the earthquake population. The physical process that underlies this discriminant is the preferential excitation of P energy relative to S energy by explosions. The exact mechanism is not fully understood so its implementation in new regions has relied upon some known explosion sources for calibration (Gitterman and Shapira, 2001).

3.3.3 Time varying spectral estimates Mining blasts conducted with a regular pattern of delays between individual explosions in the blast can exhibit interference effects which result in a repeated frequency domain pattern of high spectral values transitioning to low values known as scalloping (Bell and Alexander, 1977; Baumgardt and Ziegler, 1988; Hedlin *et al.*, 1989). These scallops are not confined to the main arrivals but persist into the P and S coda and can be visualized using time varying spectral estimates (Bell and Alexander, 1977; Hedlin *et al.*, 1989). The effectiveness of this identification procedure depends on the details of the actual blasting practice as well as the bandwidth of the observational data. Long delays produce interference effects that begin at low frequencies, while short delays manifest themselves at higher frequencies that are rapidly attenuated by wave propagation to regional distances. The utilization of high frequencies for identification has led to proposals for inclusion of seismic stations within active mining regions.

3.3.4 Low frequency modulations While time-independent spectral modulations due to millisecond intershot delays exist at high frequencies (generally above 10 Hz) recent work by Baumgardt & Ziegler (1988), Hedlin *et* al. (1990) and Gitterman and van Eck (1993) has revealed significant spectral modulations below 10 Hz. Further discussion of this point can be found in section 2 of this report.

3.3.5 Correlation analysis Recognizing seismic signatures from a particular mine provides an additional tool for characterizing an event. Such a procedure relies on empirical signals from a single mining operation. Different blasts from an operation must provide repetitive signals for the procedure to be useful. Harris (1991) has illustrated this technique in a single mine while other authors (e.g. Riviere-Barbier and Grant, 1993) have used the technique for identifying different mines in a mining region. Without detailed information from cooperating mines, it is not known if these correlation methods identify distinct mines, portions of mines, or mining practices.

3.3.6 Time-space clustering Time and space clustering of mine-related seismic events are commonly observed (e.g. Sorrells *et al.*, 1997) in regional studies. Although these characteristics cannot be used for event identification, they can be supportive of a source interpretation. An event that has the characteristics of a mining explosion but occurs during the nighttime hours would be subject to increased scrutiny. Alternatively, an event that occurs at a known mine location might not be immediately eliminated from further analysis.

3.3.7 Acoustic and seismic signals In the 1950's and 1960's there was considerable research dealing with in the infrasonic energy produced by atmospheric nuclear tests (McKisic, 1996a, 1996b, 1997). With the advent of the Limited Test Ban Treaty (LTBT) in 1963, testing in the US and Soviet Union moved underground and seismic monitoring became the principal tool of Treaty verification. CTBT interest in small and shallow events as well as the possibility of clandestine nuclear explosions in the atmosphere

has motivated renewed interest in infrasound as a monitoring tool. Many natural or man-made events emit energy into the atmosphere and the solid Earth. Each signal type has its own limitations; thus, there is considerable interest in combining the analysis of infrasonic and seismic signals. Recently, Sorrells *et al.*, 1997, have shown the utility of combining the two types of data in a study of mining explosions in northern Mexico, southeastern Arizona, and southwestern New Mexico with seismic and infrasound arrays in Lajitas, Texas. Co-located seismic and infrasonic sensors provide the data for this discriminant. The association of infrasound signals with seismic signals can not only provide additional constraints upon the source type but combining seismic and infrasound data for purposes of location may provide some advantages.

Under the CTBT, accurate location and depth estimates remain paramount indicators of event type. Although strong, shallow, earthquakes can produce a piston-like ground displacement and excite infrasonic waves in the atmosphere (Blanc, 1989) near-surface explosions are much more efficient sources of infrasound signals. A recent study (Calais *et al.*, 1997) found infrasound ionospheric perturbations resulting from a small magnitude mine blast (magnitude ~ 3) that were comparable to those produced by the magnitude 6.7 Northridge earthquake. The relative strength of infrasound and seismic signals might provide an effective depth discriminant. The effect of regional propagation must be taken into account for both seismic and infrasound signals. Stratospheric winds have a significant effect on the acoustic wave amplitudes. Since these winds can change systematically with the seasons, the array sensitivity to mining explosions will change with the time of the year.

3.4 Problematic issues

A number of practical issues must be considered in developing a robust set of discriminants for the small to moderate size signals accompanying mining explosions. Since these events are relatively small (magnitude 4 and below) and the station density is sparse (Figure 2 of section 2 of this report), it will often be the case that the signals will have small signal to noise ratios and limited bandwidth. The propagation paths are almost totally regional and can be quite heterogeneous. This effect can significantly modify the signals propagating along different paths and must be taken into account in the interpretation (e.g. Jenkins and Sereno, 2001). There are many different types of blasting practices, which are employed by the mining industry, that affect the seismic waves. Finally, there is evidence of radical departures between design and actual blasts, even to the extent that there are accidental, simultaneous detonations of significant amounts of explosives during some, delay-fired mining explosions.

3.4.1 Small events with low signal to noise ratio It is important to quantify the size of the smallest mining explosions that will be observed at regional distances.

3.4.2 Limited bandwidth Spectral modulation from delay times between boreholes may be best observed at high frequencies while modulations attributable to source finiteness appear at lower frequencies. Waveform correlation methods become less effective at higher frequencies because of variations in propagation path effects. P_n/L_g ratios work well for separating explosions from earthquakes but only at the highest frequencies. As the seismic waves propagate, the high frequencies are attenuated, resulting in mixed performance of the different discriminants. The optimum collection of discriminants for the purposes of event identification will depend on the available station spacing. Limited bandwidth data will not necessarily result in poor discriminant performance especially if some of the tools that work at low frequencies are used to complement those using high frequencies

3.4.3 Complex regional propagation Implicit in the search for robust discriminants is the necessity that complex propagation path effects not mask source effects. Experience illustrates that propagation path

effects can dominate, such as the numerous documented structures that block the propagation of L_g. This blockage, if not taken into account, could result in identifying an earthquake as a probable explosion based upon P_n or P_g to L_g ratios (e.g. McNamara and Walter, 2001).

3.4.4 Effect of blasting practices
There are many different mining practices that utilize explosives to fracture or move rock and soil. These practices can have a strong impact on the resulting regional seismograms.

3.4.5 Anomalous mining explosions Special consideration must be given to chemical explosions which are large and impulsive in nature since it is not possible to distinguish single-fired chemical and nuclear explosion sources (Denny, 1994). Typically mining explosions are delay-fired and thus distribute the seismic energy from their individual explosions over a time window that can range from several hundred milliseconds to several seconds. These anomalies could be a source of false alarms under the CTBT. It is important to determine both how often these events occur and characteristics that allow them to be uniquely identified.

3.5 Future Work

3.5.1 Calibration experiments Key to the interpretation of the regional data from mining explosions in Wyoming has been the availability of regional seismograms from single-fired, contained explosions as well as from typical mining explosions. These single-fired explosions can be used to calibrate travel times for improved location and for calibrating waveforms expected from a contained, single-fired explosion. In order for these explosions to be useful, it is necessary to have complementary source information such as source location to within 1 km and shot time to within 0.1 sec.

Similar calibration experiments have been conducted in other regions of the world (Gitterman and Shapira, 2001). The single-fired explosions do not have to be large to be useful. It is possible to use standard mining explosions as ground truth. Shot time and location to acceptable accuracy as well as blast characteristics must be made available if these sources are to be used for calibration.

Correlation analyses suggest that regional signals from closely spaced mining explosions may correlate. Calibration events (explosions with good ground truth) could be used to help with the interpretation of these correlation data. Questions remain as to the spatial dimension and range of source variables over which this correlation analysis may be applicable.

3.5.2 Cooperation with international mining community Cooperation with the US mining industry has been used to understand the utility of regional seismic and acoustic measurements in identifying mining explosions. A number of different characterization tools have been used and assessed. It is quite possible that these same tools will be useful in other mining regions. The applicability of these tools will depend, to some extent, on the similarity of blasting practices in these other areas. It is possible that cooperative relations in other mining areas may provide additional data to assess the utility of the proposed tools. Additional tools may be developed, especially in regions that employ quite different blasting practices from those studied in this section.

3.5.3 Modeling High frequency interference effects described in this paper have been shown to result from the delay timing patterns. Low frequency effects are most likely the result of temporal and spatial finiteness of the source. One would expect that under similar blasting practices, these same effects would be observable in other regions.

Numerical models of blasting that include contributions from individual explosions, spall and material cast into the pit are being developed (Barker *et al.*,1993; McLaughlin *et al*, 1993; Bonner *et al.*, 1996; Anandakrishnan *et al.*, 1997). These models may provide insight into the generation of intermediate and high frequency Lg and long period Love and Rayleigh waves.

A physical understanding of correlation analysis for different shots from the same mine will depend to some extent on the variability of regional signals introduced by differences in source function. A single mine may practice several different blasting practices that will affect the regional observations. The spatial dimensions of the sources may become important, especially in large cast blasting operations where a single source dimension can exceed 1 kilometer. The importance of variations in the waveforms introduced by differences in spatial location of the source will also need quantification. Results of correlation of single-fired explosions suggests that this may be a dominant effect. Modeling of these source and propagation effects should aid in the interpretation of the observational data sets. Constraints of the models are possible where there is good ground truth information.

3.5.4 Combining monitoring technologies Much work needs to be done to assess the value of infrasound signals for small-event identification and to make the most of the complementary nature of infrasound and seismic signals. Although significant advances in the simulation of infrasound propagation through a dynamic medium have been made (e.g. Collins *et al.*, 1995), research remains to be done on the quantification of the bias in signal strength and arrival direction caused by wind. A better understanding of what kinds of small man-made and natural events produce significant infrasound signals and how much of the source signature survives propagation through a dynamic atmosphere is needed. Simulation experiments and source observations should accompany basic research into background infrasound noise levels and improvements in sensor and array design.

3.5.5 Understanding anomalies The simultaneous detonation of many boreholes in a standard mining explosion will lead to abnormally large peak amplitudes and waveform characteristics matching those from a single-fired explosion. The seismic and acoustic observations allow the quantification of the process. Further cooperation with the mining industry is needed to understand this problem and attempt to eliminate it.

3.6 Conclusions

Mining explosions are sources of seismic and acoustic energy that are readily observable at regional distances. There is some indication that these events will primarily be constrained to known active areas of mining. The magnitudes of these events will occasionally exceed magnitude 4 with the vast number of events below this magnitude.

Broadband seismic and acoustic signals will permit the most robust event identification. A number of different identification tools have been described that take advantage of information in a variety of frequency bands. For example, the ratio of high frequency P energy to intermediate and low frequency surface waves appears to identify large surface cast blasts. High frequency spectral peaks indicative of delay firing are found to occur under some blasting conditions. Where these high frequency spectral peaks do not exist, low frequency spectral modulations associated with source finiteness can be useful.

A collection of analytical tools designed explicitly for discriminating mining explosions will provide the most robust identification of this class of seismic and infrasound events. The success of individual discriminants will depend on the interplay between the blasting practices in the mines and the regional wave propagation characteristics. Evidence has been given of situations where some individual dis-

criminants fail but the collection is able to identify an event as a mining blast. Each region will require a tailored suite of discriminants. This review has used signals recorded within 400 km of the source and thus includes a fuller set of discriminants than are likely to be useful in some sparsely instrumented regions that will require lower frequency methods. By chance, or by design, some regions will be monitored at near-regional range and will need a suite of identification tools that include techniques that take full advantage of broadband data.

Two additional discriminants are described. The first is the surface wave to body ratio for identifying cast blasts. Empirical evidence has been given for this discriminant in the Powder River Basin, possibly linking the surface waves to the material cast into the pit and the total source duration. This tool needs to be put on a firmer physical basis. The second discriminant is the intermediate to low frequency modulations observed in delay-fired explosions. The spatial and temporal finiteness of the source has been linked to this observation although the exact cause still awaits refinement. Physical modeling of the processes accompanying mining explosions may provide a mechanism for dissecting these complex events and ultimately explain routinely observed, and as yet not fully understood features (such as low frequency modulations) and features which are expected and sometimes not observed (such as high frequency modulation). Physical modeling will permit a better understanding of the effects of blasting anomalies on regional signals.

The utility of infrasound signals for both event identification and location needs further investigation. There are a number of observations that suggest that the combination of seismic and infrasound data may help identify some mining events and provide improved location estimates. Infrasound monitoring in a region with high (and possibly seasonal) stratospheric winds will need investigation. Zonal winds are strong and seasonal in Wyoming making the investigation of these effects possible in this region using data from PDAR. Over the course of a year it will be possible to monitor mine blasts under good and poor wind conditions. In addition, the site provides numerous sources of near-surface, variable, wind noise.

Critical to this study has been the availability of calibration data for the purposes of assessing different discriminants. Single-fired contained explosions were conducted at a mine. Similar experiments can be conducted in a cost-effective manner in other mining regions around the world providing the necessary information for developing robust discriminants.

The proposed discriminants need to be tested in an operational setting. Such an exercise will allow us to learn why promising discriminants will sometimes fail - either due to problems at the source (e.g. sympathetic detonation) or during propagation (e.g. high attenuation).

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